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of

THE ROYAL AERONAUTICAL SOCIETY

MAY 1955

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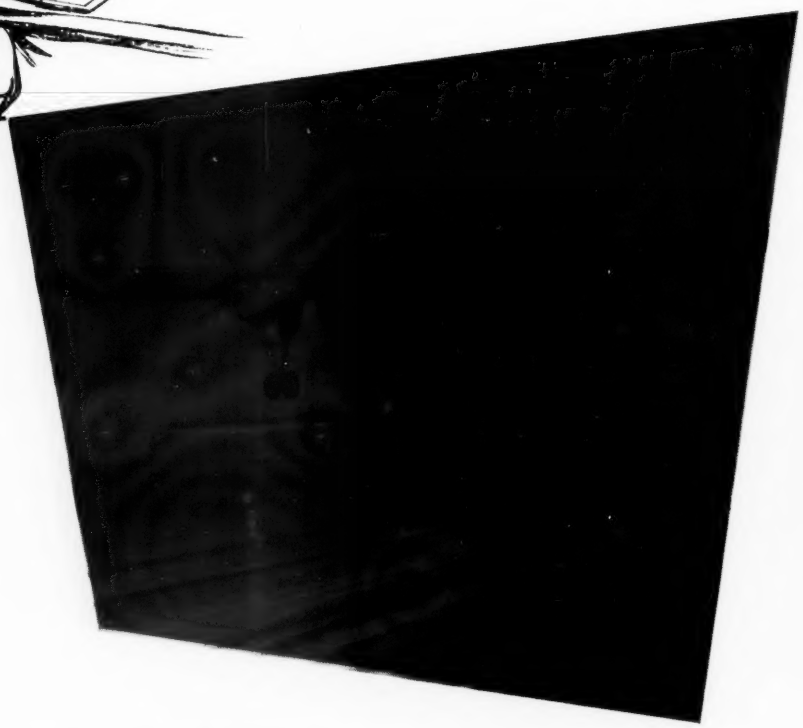

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ADDITIONS TO THE LIBRARY. REPORTS.

All communications for publication in, and advertisements for, the JOURNAL *should be addressed to the Editor,* JOAN BRADBROOKE, *A.R.Ae.S.; all communications on general matters affecting the Society should be addressed to the Secretary,* A. M. BALLANTYNE, *T.D., B.Sc., Ph.D., A.F.I.A.S., A.F.R.Ae.S.*

None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.

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Mr. N. E. Rowe

President 1955-56

AFTER serving his apprenticeship in Marine Engineering at Devonport Dockyard and serving in the First World War, Mr. Rowe attended City and Guilds (Engineering) College, holding a Royal Scholarship and Whitworth Exhibition. He gained his A.C.G.I. and B.Sc. and, in 1924, after post-graduate work in Hydro-Electric Engineering, a Diploma of the Imperial College.

From 1924 to 1940, he was employed by the Air Ministry, working at Farnborough, Martlesham Heath and London and in 1940 joined the Ministry of Aircraft Production, becoming Director of Technical Development, in 1941, and Director-General of Technical Development in 1945.

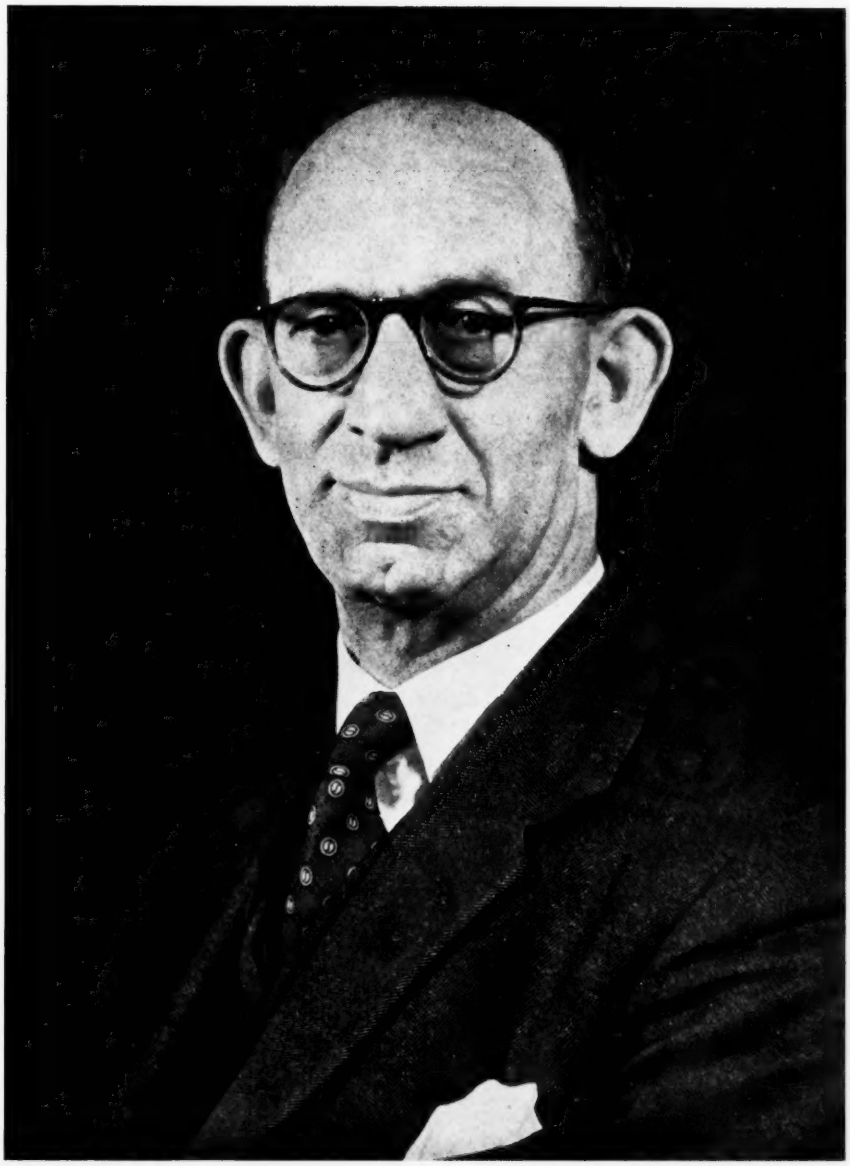
In 1944, he was awarded the C.B.E. for work in the Ministry of Aircraft Production.

From 1946 to the end of 1951, Mr. Rowe was the Controller of Research and Special Developments, British European Airways, and then joined Blackburn and General Aircraft Ltd. as Technical Director.

He has read lectures to the Royal Aeronautical Society, the Helicopter Association, the Institute of Transport (Bristol and White-Smith Air Transport Medal, 1952) and at a Joint Meeting of the Institute of the Aeronautical Sciences and Society of Automotive Engineers in New York.

Mr. Rowe was elected a Fellow of the Society in 1942, and has been a Member of Council since 1942. He is a Member of the Council of the Helicopter Association, a Fellow of the Institute of the Aeronautical Sciences, a Member of the Institution of Mechanical Engineers, a Member of the Institute of Transport and a Fellow of the Royal Society of Arts. He had conferred upon him the Fellowship of the City and Guilds of London Institute (F.C.G.I.) in January this year.

Mr. Rowe takes office as President at the Annual General Meeting on 5th May, 1955.



N. E. ROWE, C.B.E., *Fellow*
Wh.Ex., A.C.G.I., B.Sc., D.I.C., M.I.Mech.E., F.C.G.I., F.I.A.S.

President 1955-6

NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

Whitsun Holidays

The Offices and Library of the Society will be closed from Friday afternoon, 27th May, until Tuesday morning, 31st May 1955.

43rd Wilbur Wright Memorial Lecture

The 43rd Wilbur Wright Memorial Lecture will be held on Thursday 19th May 1955 at 6.0 p.m. at the Royal Institution, 21 Albemarle Street, W.1. Tea will be served at 5.30 p.m.

The subject of the lecture is " Flight Control " and the lecturer will be Dr. C. S. Draper, F.I.A.S., of Massachusetts Institute of Technology.

Library

The Library of the Society will be closed on 1st, 2nd and 3rd June.

Associate Fellowship Examinations

The Associate Fellowship Examinations in the old and Revised Syllabus will be held in the offices of the Society on 1st, 2nd, 3rd June. Full particulars will be sent direct to all Candidates.

Diary

LONDON

19th **May**
The 43rd Wilbur Wright Memorial Lecture.—Flight Control. Dr. C. S. Draper. The Royal Institution, Albemarle Street, W.1. 6 p.m. (Tea 5.30 p.m.)

21st May
Graduates' and Students' Section. — Visit to Hawker Aircraft Ltd.

BRANCHES

11th **May**
Chester.—Annual General Meeting. The Grosvenor Hotel, Chester. 7.30 p.m.

12th May
Glasgow.—Aviation Fuels. C. F. Holloway. Royal Technical College, Glasgow. 7.30 p.m.

16th May
Halton.—Films. Branch Hut, R.A.F., Halton. 6.45 p.m.

18th May
Hatfield.—Annual General Meeting. de Havilland Restaurant, Hatfield. 6.15 p.m.

23rd May
Halton.—Dynamic Heating (the heat barrier). Sqdn. Ldr. P. C. Cleaver, O.B.E. Branch Hut, R.A.F., Halton. 6.45 p.m.

25th May
Halton.—Visit to High Duty Alloys, Slough, Bucks.

13th **June**
Halton.—Modern Aircraft Electrics. Branch Hut, R.A.F., Halton. 6.45 p.m.

20th June
Halton.—Films. Branch Hut, R.A.F., Halton. 6.45 p.m.

27th June
Halton.—Junior Members' Night. Discussion on Problems of High Speed Flight. Branch Hut, R.A.F., Halton. 6.45 p.m.

4th **July**
Halton.—The Medical Aspects of Aircraft Engineering. Wing Cdr. Latham. Branch Hut, R.A.F., Halton. 6.45 p.m.

Annual General Meeting, 5th May 1955

Members are reminded that the Annual General Meeting of the Society will be held in the offices of the Society at 5.30 p.m. on 5th May 1955. The Agenda and Annual Report were published in the April Journal.

News of Members

E. W. Absolon (*Graduate*) has been appointed Deputy Chief of the Engineering Research Department at Gloster Aircraft Co. Ltd.

A. J. K. Carline (*Associate Fellow*) has been appointed Chief Technician of Hunting Percival Aircraft Ltd. responsible for the direction and co-ordination of all technical work on the Company's projects.

F. J. Delves (*Associate Fellow*) has been awarded the Medaille de l'Aéronautique.

J. Hanson (*Fellow*) has been appointed Chief Superintendent of the Aeroplane and Armament Experimental Establishment at Boscombe Down.

Wing Cdr. A. M. D. Howes (*Associate*) has been appointed Regional Representative of the East Africa Directorate of Civil Aviation in Tanganyika.

E. D. Keen (*Fellow*) has been appointed Chief Designer of Sir W. G. Armstrong Whitworth Aircraft Ltd. He was formerly Assistant Chief Designer.

T. H. Lindbom (*Associate*) has left A. V. Roe of Canada and has taken up a position as Senior Engineer—Controls at the Stratos Division of Fairchild Engine & Airplane Corporation, New York.

J. Lloyd (*Fellow*) has retired from his position of Technical Director of Sir W. G. Armstrong Whitworth Aircraft Ltd., but retains his seat on the Board of Directors.

S. W. D. Lockwood (*Associate Fellow*) has been appointed Works Director and General Manager of Sir W. G. Armstrong Whitworth Aircraft Ltd.

C. L. Paice (*Associate Fellow*) has left the English Electric Company, Luton, and has been appointed Senior Engineer at Pye Ltd., Cambridge.

Flt. Lt. J. N. Quick (*Associate Fellow*), recently a Lecturer in Aerodynamics and Thermodynamics, has been posted to the Shell Film Unit as Technical Adviser in connection with films on high speed flight.

D. J. Saunders (*Associate Fellow*), formerly of the Rocket Propulsion Department of the Ministry of Supply, has joined the Compoflex Co. Ltd. as Chief Development Engineer (Hydraulics).

H. J. Staite (*Associate Fellow*) has been appointed Chief Research Engineer, Sir W. G. Armstrong Whitworth Aircraft Ltd.

A. J. Troughton (*Associate Fellow*), formerly Deputy Chief Technician, Sir W. G. Armstrong Whitworth Aircraft Ltd., has been appointed Chief Technician.

Henry R. Watson (*Associate Fellow*) has been appointed Technical Director of Sir W. G. Armstrong Whitworth Aircraft Ltd., and a Member of the Board. He was formerly Chief Designer.

D. Á. Woodley (*Associate Fellow*), formerly Chief Technician, Sir W. G. Armstrong Whitworth Aircraft Ltd., has been appointed Assistant Chief Designer (Technical).

Journal Premium Awards

The following Premium Awards have been made for Papers and Technical Notes published in the Journal in 1954:—

Messrs. G. C. I. Gardiner and P. Brett for their paper on Propellers for High Speed Aircraft. (December 1954 Journal.)

Mr. F. B. Greatrex for his paper on Air Intake Efficiency. (September 1954 Journal.)

Mr. R. Tourret for his paper on Foaming and Aeration of Oils in Aviation Power Plant. (January 1954 Journal.)

Mr. G. Orloff for his paper on The Development of the 4,000 lb./in.^{2} Hydraulic System. (March 1954 Journal.)

Messrs. R. B. Adler and S. J. Fricker for their paper on Notes on the Flow of Scheduled Air Traffic. (July 1954 Journal.)

Mr. K. G. Wilkinson for his paper on Progress in Sailplane Design. (July 1954 Journal.)

Mr. G. Forrest for his paper on Internal and Residual Stresses in Wrought Aluminium Alloys and their Structural Significance. (April 1954 Journal.)

Mr. H. L. Cox for his paper on Computation of Initial Buckling Stress for Sheet Stiffener Combinations. (September 1954 Journal.)

Dr. R. E. D. Bishop for his paper on The Analysis and Synthesis of Vibrating Systems. (October 1954 Journal.)

Mr. A. P. Kennedy for his paper on A Method of Determining the Safe Life of an Aircraft Wing from Fatigue Test Results. (May 1954 Journal.)

Mr. A. H. Chilver for his paper on The Estimation of Fatigue Damage in Aircraft Wing Structures. (June 1954 Journal.)

Mr. K. L. C. Legg for his paper on Integral Construction—A Survey and an Experiment. (July 1954 Journal.)

Dr. J. H. Preston for his paper on The Determination of Turbulent Skin Friction by Means of Pitot Tubes. (February 1954 Journal.)

Mr. E. J. Catchpole for his paper on The Optimum Design of Compression Surfaces having Unflanged Integral Stiffeners. (November 1954 Journal.)

Mr. F. G. Irving and Mr. R. A. Saunders for their Technical Note on The Use of Glass Cloth/Resin Moulded Compounds in the Laboratory. (February 1954 Journal.)

Mr. A. C. Nicholls for his Technical Note on Empirical Formulae for the Determination of Stress Curves. (October 1954 Journal.)

Mr. F. A. MacMillan for his Technical Notes on Viscous Effects on Pitot Tubes at Low Speeds and Viscous Effects on Flattened Pitot Tubes at Low Speeds. (August and December 1954 Journals.)

Mr. P. R. Payne for his Technical Notes on A Method of Rapidly Estimating Propeller Moment and The Flight Envelope of the Helicopter. (April and November 1954 Journals.)

Elections

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

John Desmond Booker
Robert William Warren Buckley (*from Associate*)
Harry Balshaw Caldwell
Alan Trevor Ching (*from Associate*)
Bertram Frank Clark
Peter Falcon Clayton
Francis Charles Drinkwater (*from Graduate*)
Ralph Gordon Evans (*from Graduate*)
Peter Goodwin Fielding (*from Associate*)
Edward Glodeck
Robert Bellwood Greenhow
Morris Vivian Jenkins (*from Graduate*)
David Anthony Jermyn (*from Graduate*)
Raymond Charles Kenderdine
Richard Alvin Mathias Lewis (*from Graduate*)
Peter Edward Thomas Oakley (*from Graduate*)
Ronald David Page (*from Student*)
Edward Albert Ridge (*from Graduate*)
Duncan Menzies Soutar Simpson (*from Graduate*)
Josef Singer (*from Graduate*)
Charles Clayton Sumbler
Robert Graham Taylor (*from Graduate*)
Roy Thompson-Holland (*from Graduate*)
Frank Joseph Thornton
Arthur Frank Albert Watts (*from Graduate*)
Edward Donald Wynn (*from Associate*)

Associates

Bryan Musgrave Collings (*from Student*)
Cyril Fleisher (*from Student*)
Royle Bernard Denis Jansen (*from Graduate*)

Graduates

Bernard George Ambrose (*from Student*)
Frank Bennison
Clifford Lester Bore (*from Student*)
Anthony Gerald Dean
Roy Edward Dunford
John Ernest Felstead (*from Student*)
Brian Keith Glenister (*from Student*)
Bhagwant Singh Grover
Simon McNab Humphry (*from Student*)
Eric Antony Robert Humpston (*from Student*)
Brian Kaye Knight (*from Student*)
Deep Chand Kohli (*from Student*)
Denis Little
William Wallace Muir
Kenneth George Paul (*from Student*)
Arthur Allan Powell
Peter Hubert Swift (*from Student*)
Myrddin Pryce Thomas

Students

Kuldeep Sungh Chowdhury
Alan Richard Farr
John Morgan Hatfield
Thomas Johnston
Kenneth Gerald Frank Noble
Ronald George Maynard Scarfe
David James Stewart
Allan Charles Willmott
James Lindsay Wood

Companion

Victor Charles Pickett (*from Student*)

Correction—January Journal

It is regretted that in the paper on "The Evolution of Arctic Airways" in the January Journal, Resolute and Alert airfields were described (p. 24) as belonging to the North Eastern Command of the U.S. Air Force. In fact they are Canadian bases, Resolute being an R.C.A.F. base and Alert under civil control; the weather stations at both are operated jointly by Canada and the United States and they are within the area over which North Eastern Command operates.

Wing Commander W. R. Hartwright

After spending his schooldays at New College School and Magdalen College School, Oxford, Wing Commander W. R. Hartwright was granted a Short Service Commission in the Royal Air Force in 1927 (General Duties). On completion of his training he was posted to the Fleet Air Arm and served in H.M.S. *Courageous* and H.M.S. *Furious*.

In 1932 he was granted a Medium Service Commission, and in 1936 Wing Commander Hartwright was given a Permanent Commission in the R.A.F. From 1932 to 1939 he was a Flying Instructor with the Fleet Air Arm, specialising in instructing in deck landing and catapulting.

At the outbreak of war he was serving with 101 Squadron, and in 1941 he was sent to Australia on attachment to the Royal Australian Air Force, at Archerfield, Brisbane, and Maryborough. He returned to England in 1943, and held various administrative posts until in 1948 he fell ill and spent more than a year in hospital and convalescing.

He was retired from the R.A.F. in 1950, no longer fit for full flying duties.

In March 1953 Wing Commander Hartwright joined the staff of the Society, and soon became " Dickie " to many. He took over the work of many of the Committees of Council, and soon became known to many of the members of the Society through his work on the Branches and Lectures.

" Dickie " Hartwright, despite his handicap of ill-health, never complained; and he was always courteous and willing.

In March 1955 he took a bronchial cold, and on the 24th of the month he passed away peacefully in his sleep. Wing Commander W. R. Hartwright, who was 45 years of age, left a widow and one daughter, to whom all his friends in the Society extend their deep sympathy.

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 59 MAY 1955 NUMBER 533

The Prospects and Problems of Rocket Propulsion for Aircraft

by

A. D. BAXTER, M.Eng., M.I.Mech.E., F.Inst.Pet., F.R.Ae.S.

(Professor of Aircraft Propulsion, College of Aeronautics)

The 938th Lecture to be given before the Royal Aeronautical Society was the Eighteenth Main Lecture to be held at a Branch and was given before the Isle of Wight Branch on 10th February 1955. Mr. H. Knowler, F.R.Ae.S., Chairman of the Branch, and Mr. N. E. Rowe, C.B.E., A.C.G.I., B.Sc., F.C.G.I., F.I.A.S., F.R.Ae.S., President-Elect of the Society, presided.

MR. H. KNOWLER: It was his pleasant duty as Chairman of the Isle of Wight Branch to hand over to the Society's Chairman, but before doing so he must apologise for the unavoidable absence of Sir Sydney Camm, President of the Society; and also, Sir Arthur Gouge, who was abroad.

Now he wished to welcome the visitors; first Mr. N. E. Rowe whom they knew well because he had been the Chairman of the Branches Committee for a good many years and had taken so much interest in all the Branches. They probably knew that he was the President-Elect of the Society and they were honoured by his taking the Chair. He also welcomed Dr. Ballantyne and his team from the Secretariat of the Society. He was very pleased to see many members of the Main Society, of the Isle of Wight Branch, and visiting members from a number of other Branches, including representatives from Southampton, Portsmouth, Hatfield, Luton, and Boscombe Down.

MR. N. E. ROWE: He was very sorry that the President was not with them because these occasions when, as it were, the Main Society came out to the Branch were very important and he knew that only the most urgent business kept the President away. The practice of giving Main Lectures of the Society in the Branches had been running for about five years, but he thought this was the first to be held at this Branch and he was delighted to see such a splendid audience and to see such obvious interest and also to hear of the attendance of representatives from other Branches.

They were privileged that night to hear from Professor Baxter of the College of Aeronautics. He was one of the first in this country to work on gas turbines for aircraft and he had an intimate knowledge of the whole subject. After graduating from the University of Liverpool, Professor Baxter worked with the Daimler Company from 1930 to 1934; he was a research engineer at the Institute of Automobile Engineers from 1934 to 1935 and then went to the Royal Aircraft Establishment where he was a Technical Engineer on the gas turbine research and later, on rocket propulsion research. He became Superintendent of the Rocket Propulsion Department from 1947 to 1950 and since 1950 had been Professor of Aircraft Propulsion at the College of Aeronautics at Cranfield.

Introduction

The successful development of the gas turbine for aircraft propulsion stimulated much thought, some serious and a great deal speculative, on the possibilities of even more advanced forms of propulsion. The ram-jet and the rocket immediately sprang to mind. The former was a natural development of the turbo-jet. It could extend the useful field of the turbo-jet but the bounds of that extension could be clearly seen. On the other hand, the rocket was not restricted by the same fundamental limitations and its eventual, although still somewhat remote, exploitation in wider spheres could be prophesied with some confidence.

Before the 1939-45 War, the stage of development of the rocket motor was comparable with that of the internal combustion engine a century ago. Pioneers like Tsiolkovski in Russia, Esnault-Pelterie in France, Oberth in Austria and Goddard in America had laid down the basic theory and made some small scale experiments in support, but the first major practical steps came from the Germans during the war. They demonstrated the potentialities of rocket propulsion very effectively and pointed the way to future developments. As a result, post-war progress has been greatly accelerated, but unfortunately much of it has been shrouded in secrecy. Nevertheless, it is probably fair to liken the present status of the rocket motor to that of the petrol engine in the early days of powered flight. The latter, only forty years ago, was recognised as a practical, but comparatively inefficient, aircraft power plant; its usefulness was limited and its future possibilities, except as a weapon of war, were no more than visions rejected by the great majority.

It is not surprising, therefore, to find that only two Main lectures of the Society have been devoted to the subject of rockets. The first, by Perring[1] reviewed the wartime German work, and the second, by Cleaver[2], revealed some lines of development with particular reference to assisted take-off. The present paper endeavours to follow up these earlier ones by considering the possible roles of the rocket motor in the near future and by putting forward some of the problems which must be solved before the more ambitious proposals can be achieved. The discussion will be confined to earth-bound piloted craft, although there is much in common both with guided weapon propulsion and the requirements of interplanetary flight.

Notation

A_t nozzle throat area
a weight of items which are independent of pressure
b constant depending upon operating pressure
E thrust
I specific impulse (lb./lb./sec.)
K universal gas constant = 2,778 ft. lb./°C. lb. mole.
L^* length of chamber = (V_c/A_t)
M molecular weight of combustion per lb.
P_1 combustion gas pressure (lb./ft.² abs.)
P_2 exhaust gas pressure (lb./ft.² abs.)
q specific propellant consumption including turbo-pump consumption (lb./hr./lb.)
T_1 combustion gas temperature (°K.)
t operating time
V_c combustion chamber volume
v jet velocity (ft./sec.)
W_m motor weight
W_p propellant weight
γ ratio of gas specific heats at constant pressure and volume
η an empirical efficiency factor $\approx 0{\cdot}9$

Comparative Performance

To determine the best uses of the rocket motor, it is first necessary to consider its special features, particularly in relation to the corresponding characteristics of other propulsion units. They can be enumerated as:—

(*i*) thrust practically independent of altitude and forward speed.

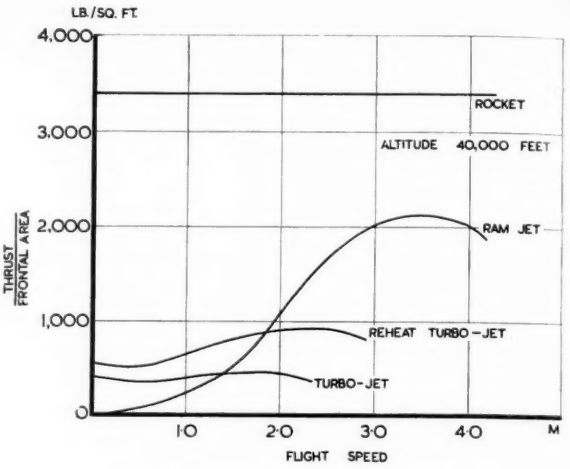


FIGURE 1. Variation of thrust with forward speed.

(*ii*) thrust/weight and thrust/frontal area ratios very high.
(*iii*) specific consumption very high.

The first and second features are illustrated in Figs. 1 and 2. Fig. 1 compares thrust per square foot of frontal area at varying forward speed and a constant altitude of 40,000 ft. for the rocket and the air-swallowing jet engines. It will be seen that under these circumstances the rocket has almost twice the thrust of the ram-jet, even at its peak performance, and approaching four times the best the turbo-jet can give with reheat

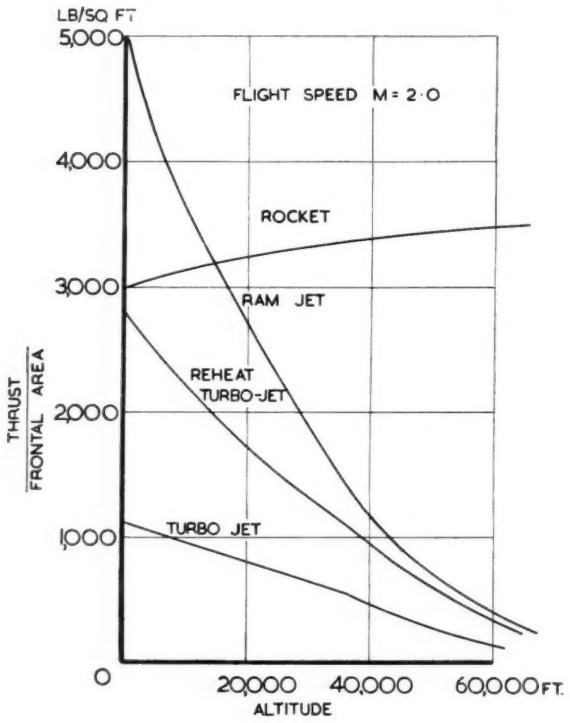


FIGURE 2. Variation of thrust with altitude.

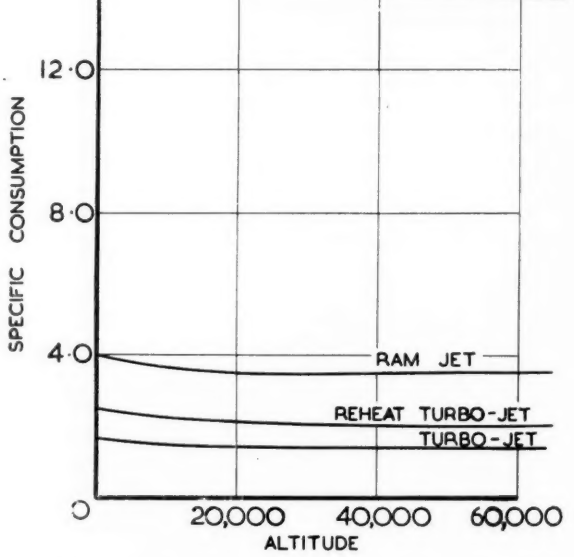


FIGURE 3. Specific fuel consumption of high speed power plants.

to the maximum temperature. Fig. 2 gives the same comparison for varying altitude and a constant speed of $M=2{\cdot}0$. The decreasing thrust of the air-swallowing engines becomes serious above 60,000 ft., and very little net thrust is produced but, in contrast, the rocket has increased its thrust by 15 per cent. or more. Near ground level the difference is not so marked, and a well designed ram-jet could give more thrust than the rocket. Generally, however, high supersonic flight speeds near the ground are unlikely because of aircraft stressing considerations.

It should also be borne in mind that to obtain the optimum performance over a range of flight speeds calls for variable intake geometry and exhaust nozzle shape for both ram-jet and turbo-jet. To do this may involve considerable extra weight and mechanical complication and generally it will be preferred to design for a specified flight speed and accept a reduction in performance at other conditions. The rocket does not suffer intake problems at all nor are exhaust expansion ratios affected by forward speed. Thus its relative thrust will tend to be better than the figures indicate.

The thrust/weight ratios follow the same curves and can be compared by suitable modification of the scales, which will be different for each engine. The ratios are usually quoted in the inverse form and present-day turbo-jets have weight/thrust ratios of about 0·3 at static sea level conditions, rising to 0·75 at 30,000 ft. and 3·0 at 60,000 ft. Rocket motors, on the other hand, should be not more than 0·06 at all altitudes; that is, up to fifty times lighter than the turbo-jet. With reheat, the turbo-jet specific weight would be between 50 per cent. and 66 per cent. less. Little information on the weight of ram-jets is available and they are difficult to compare because of the large variation in thrust with forward speed. At sea level, $M=2$, they will probably be lighter than rockets, but at 60,000 ft. they will be 8 to 10 times heavier.

To complete the picture, the third feature, specific propellant consumption, must be considered. Its variation with altitude is given in Fig. 3 for the various engines, and it is at once apparent that this is the rocket's one serious drawback, which makes its use as a conventional power plant almost impossible. This large propellant weight penalty is, however, more than compensated by the low motor weight for short times of operation and Fig. 4 shows the running times and altitudes for which it has an advantage over the best that a reheated turbo-jet will give. Without reheat the "break-even" times would be approximately double those shown and in both cases the time is increasing rapidly with height. Some virtue may be claimed, too, for the rocket because the final weight of an aircraft of the same initial weight would be much less than for the turbo-jet version.

Aircraft Uses

In view of the limited time of operation for which the rocket gives a lower total weight, it may be asked why it should be considered at all. Unless it has some potential advantages, there is no case for it and, considered merely as one propulsion unit replacing another for straightforward flight, it obviously has a very limited claim. This direct substitution is a trap that has caught designers more than once in the past with other forms of engine, and it is essential to compare them when each is installed in the most appropriate airframe and is using

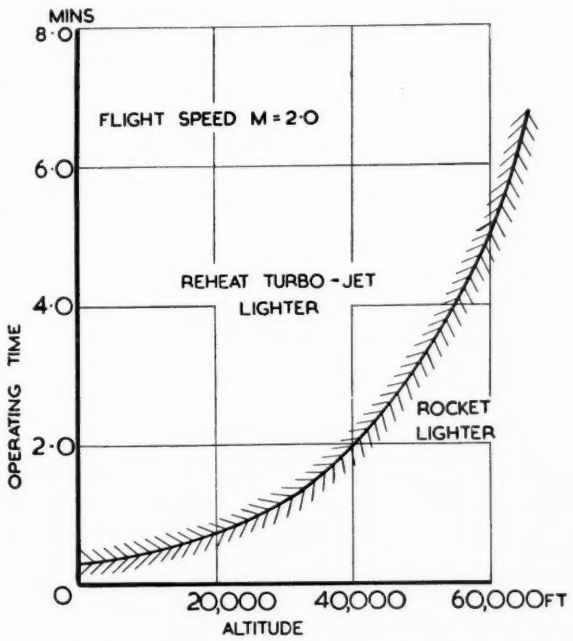


FIGURE 4. Break-even times at which weights of rocket and propellant equal those of fully reheated turbo-jet.

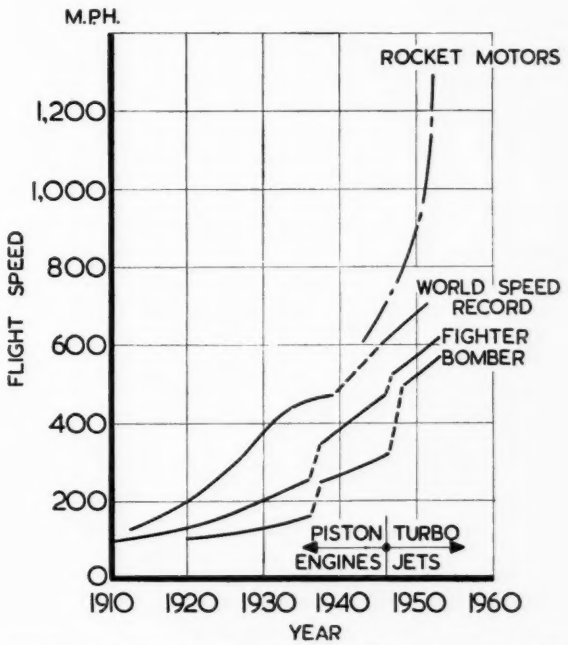


FIGURE 5. Increases in maximum speed (based on diagram by Sir Harry Garner[3]).

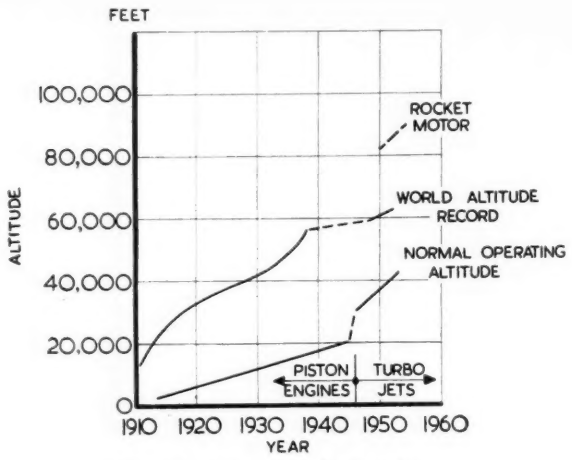


FIGURE 6. Increases in flight altitude.

its optimum flight plan. For the rocket, this will demand new and unorthodox operating techniques.

The rocket's main advantages, on the evidence of Figs. 1 and 2, are that it can develop larger thrusts at greater altitudes and higher speeds than any other form of power plant. There is an obvious military value in this, but it may be questioned whether civil aircraft will find the same value. An examination of aircraft performance from the earliest days shows how average speeds (Fig. 5) and operating altitude (Fig. 6) have followed the continually increasing records set up by specially prepared engines and aircraft. The fighter aircraft speeds have been the record speeds of 8 to 10 years previously, and the bomber speeds have followed the fighters a few years later. In the past, too, civil transport has been close behind the bomber and is still continuing to follow on its tail. It will be observed how the rocket-propelled aircraft fit into the diagrams, suggesting the beginning of a new era. Extrapolating from the record curves may be an uncertain way of predicting the future, but there is no reason to assume that higher speeds and altitudes will not be attempted and successfully accomplished. When this occurs it will open the way for others to follow and the upward slope of all the curves will continue.

This is not the place for philosophical reasoning on the wisdom or foolishness of the constant striving after greater speeds, but only to remark on the trend which has existed since the earliest days and still continues without any sign of stopping in spite of the so-called "barriers" which exist. The sonic "barrier" no longer presents the formidable problems of ten years ago, and no doubt the thermal "barrier" will diminish as it is approached, although the way in which it will be surmounted may involve quite unexpected techniques. For some time to come, the air-swallowing turbo-jets and ram-jets will be able to provide sufficient thrust to drive aircraft at higher speeds, although the prospects for greater altitudes are limited. Eventually a stage will be reached where they will be restricted by stagnation temperature rise or by lack of air for combustion. At this stage a rocket motor will have to take over. This will be the ultimate field for the rocket motor, but many benefits may be obtained from it before that point has been reached if it is used in combination with the other power plants, rather than in competition. By a judicious arrangement it should be possible to make the most of the good features of both and avoid most of the drawbacks.

From its characteristics, it can be deduced that the main role of a rocket motor should be to act as an accelerating unit rather than as one for steady flight. Thus the duties for which it is most suitable at present are:—

(*i*) assisted take-off,
(*ii*) climb boosting,
(*iii*) level flight acceleration.

ASSISTED TAKE-OFF

This use of rocket motors, although the antithesis of high speed and high altitude, can prove to be one of the most fruitful of present-day applications. As mentioned already, it was discussed some years ago in a broad sense by Cleaver[2], who gave examples of American, German and British units.

The main factors to be considered in take-off are aircraft wing loading, thrust loading and available distance. Generally, design performance is such that these have adequate margins, but conditions can arise where any of them may be outside normal limits. An increase in all-up weight, for instance, requires an increase in engine thrust or a longer take-off run. There is a limit to runway lengths and then the only alternative is extra thrust. On the other hand, a decrease in thrust available results from operating at low atmospheric pressures or high temperatures. With a turbo-jet, a change in altitude from sea level to 3,500 ft. would cause a loss of 10 per cent. in static thrust and a change in air temperature from 15°C. to 40°C., a loss of 15 per cent.

The effect of such losses on permissible aircraft take-off weight is shown in Table I, together with the effect of a reduction in runway length and the converse effect of over-load weight on thrust. From this it is apparent that, to provide for all contingencies, the engines must be considerably in excess of the size normally required, or some temporary thrust boosting must be provided. The latter is preferable since it avoids a large permanent increase in engine weight and any loss in efficiency

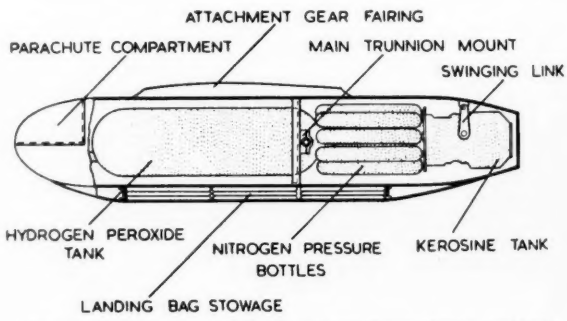


FIGURE 7. Diagram of de Havilland Super Sprite assisted take-off rocket motor in jettisonable nacelle.

TABLE I

VARIATIONS IN TAKE-OFF PERFORMANCE

All-up weight % ...	100	92	87	100	120
Take-off thrust % ...	100	85	100	128	144
Take-off distance % ...	100	100	80	80	100

associated with cruising operation at low part throttle conditions. It can be carried out to a limited extent by water injection to the engine (about 10 per cent. maximum boost) and for turbo-jets, by reheat (less than 40 per cent.). It can also be carried out to an almost unlimited extent by rocket thrust.

The reheat method carries some penalty in weight and a built-in loss which is reflected as a permanent increase in fuel consumption of some 3-4 per cent. or more. On the other hand, the rocket empty weight will not be greatly in excess of the extra weight of reheat equipment and the design may be such that the unit is jettisoned after take-off, as in the de Havilland Super Sprite (Fig. 7). The benefits obtained are clearly indicated in Fig. 8 which shows the increase in net all-up weight, *i.e.* after deducting rocket and propellant weight, for various ratios of rocket to main engine thrust. The limiting curve is given when the rocket thrust is applied throughout the full duration of take-off, but this does not represent the most efficient operating technique. If, for example, the rocket thrust is increased and applied only during the later stages of take-off, a considerable gain is effected in all-up weight for a given expenditure of propellant or, alternatively, less propellant is required for a given aircraft weight. Thus, the same amount of propellant used in the last quarter of the take-off time by a motor giving four times the thrust of one running throughout take-off, will permit an increase in take-off weight of 16 per cent. compared with 11 per cent. Increasing the thrust and reducing the time still further will give only very slight improvements as the lines of fixed propellant consumption tend to asymptotic all-up weight values.

CLIMB BOOSTING

This use may be considered as a prolongation of the assisted take-off case. Its main application must be to

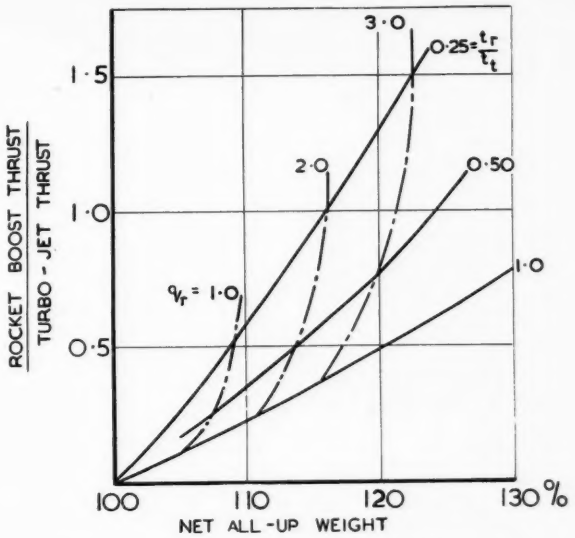


FIGURE 8. Effect of rocket thrust on aircraft weight for constant take-off distance.

enhance the climb of military aircraft. An example of this type of installation is shown in Fig. 9 which illustrates the Hawker P.1072, a modified version of the Sea Hawk, with an Armstrong Siddeley rocket motor.

The technique of using such a combination is a matter which, like the assisted take-off, can be altered to meet the requirements. The important consideration is the permissible operating time of the rocket, set either by the weight of propellant that can be carried or by tankage space available. For the fighter, these could be supplemented by an over-load of propellant in jettisonable tanks. This would not seriously affect the take-off or initial climb as the thrust/weight ratio of modern machines is high. Alternatively, rocket-assisted aircraft could be designed with a different philosophy, based on the rapid reduction in weight with flight time. For example, Table II shows a possible weight breakdown for a conventional fighter aircraft and a rocket-assisted fighter, both at take-off and landing. In both

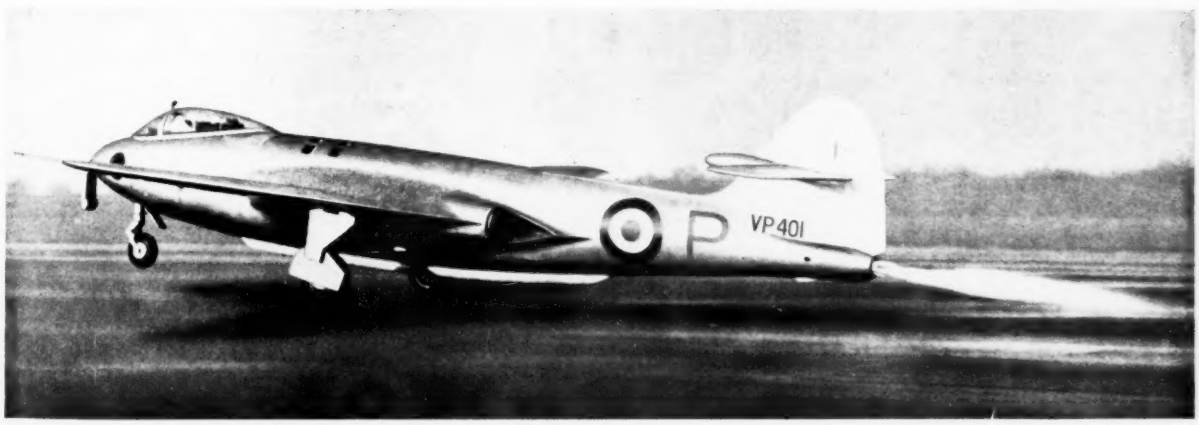


FIGURE 9. Hawker P.1072 with Armstrong Siddeley Snarler climb boost rocket motor (*see* Fig. 18).

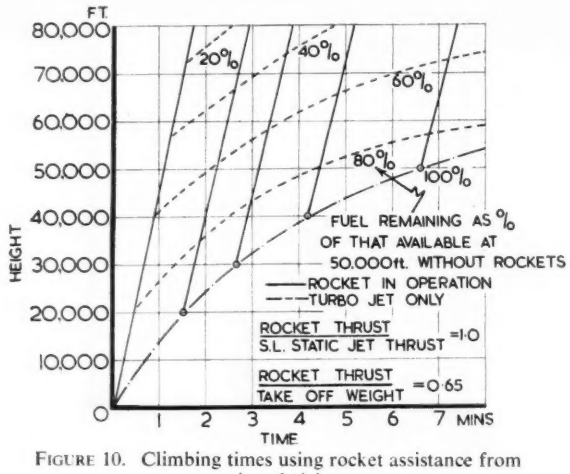


FIGURE 10. Climbing times using rocket assistance from various heights.

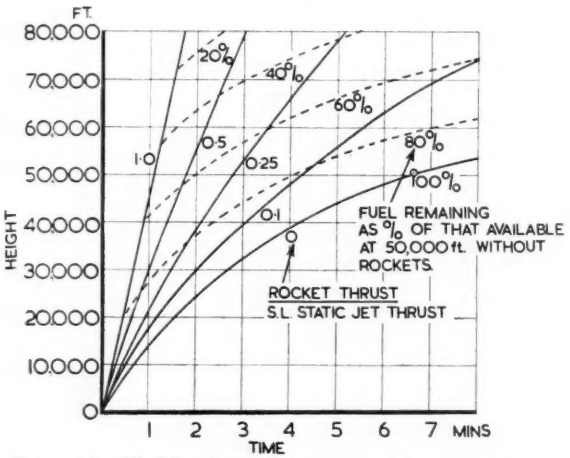


FIGURE 11. Climbing times using rocket assistance at various thrust levels.

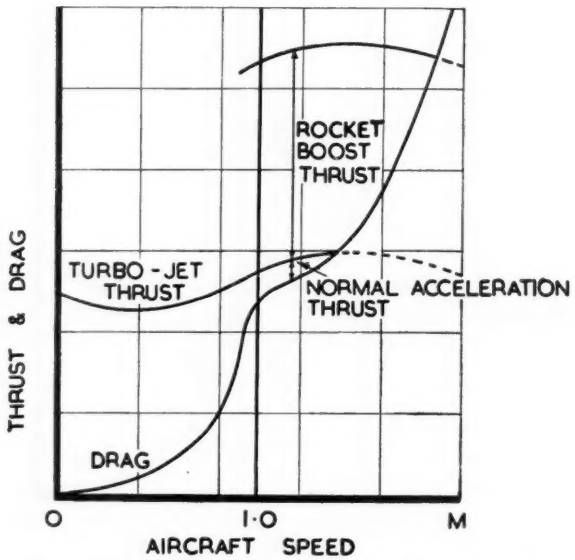


FIGURE 12. Effect of rocket thrust on aircraft acceleration and maximum speed.

cases the landing weight is the same, the only difference being in the reduction of payload and equipment to compensate for the added weight of the rocket motor. At the same time the rocket endurance is greatly extended compared with that possible by a direct exchange of rocket motor for fuel weight, which is the normal way of considering the problem.

The advantages of climb boosting are shown in Figs. 10 and 11 which give typical climb curves and the relative amounts of fuel left with different operating techniques. In Fig. 10, a rocket motor thrust equal to the turbo-jet sea level static thrust is assumed and it is started at various points in the climb. In all cases much greater altitudes can be reached than with the jet alone and the time to height is small. As a result, the fuel available for level flight is less, but the reheated jet engine endurance need not be greatly different because the lower thrust at the higher altitude will require less fuel. An alternative boosting technique is given in Fig. 11, where rockets of different thrust ratios are provided and in each case operated throughout the whole climb. There is little difference in the performance between the two arrangements, both of which are assumed to start with a power plant plus propellants weight of 60 per cent. of the aircraft weight.

ACCELERATION

Acceleration in level flight is a function of aircraft weight and excess of thrust over drag. The variation of turbo-jet thrust, including reheat and aircraft drag with flight speed, are generally of the form shown in Fig. 12. The excess thrust diminishes rapidly near sonic conditions and then remains comparatively constant to quite a high supersonic value. Thus, the maximum speed of the aircraft may be high, but its acceleration towards it will be quite slow. If rocket boost is applied during the acceleration, the thrust curves can be temporarily displaced so that the excess thrust available is an order of magnitude greater and, consequently, the time to reach the top speed greatly reduced. The effect of rocket boost in this case is shown in Fig. 13 for an acceleration from $M = 0{\cdot}9$ to $M = 1{\cdot}3$ at 50,000 ft. Without assistance the jet engines require five minutes to reach the upper speed, but even a small rocket motor will cut the time to one minute. Because of this large difference in time,

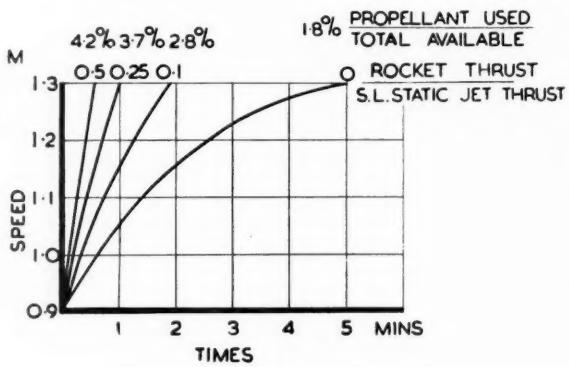


FIGURE 13. Acceleration times at 50,000 ft.

TABLE II

COMPARATIVE WEIGHTS OF SUGGESTED FIGHTER

Component % *weight*	*Normal fighter*		*Rocket-assisted fighter*	
	Take-off	*Landing*	*Take-off*	*Landing*
Structure	33	47	27	47
Turbo-jet	20	29	17	29
Rocket	—	—	3	5
Fuel and propellant	30	—	42	—
Payload and equipment	17	24	11	19
Total	100	100	100	100

the total propellant consumption in the second case will only be about twice that of the reheated turbo-jet operating alone over the longer period. In addition to reaching the normal top speed rapidly, a continuation of the boost period would permit a much higher top speed to be attained, but this would, of course, entail a penalty in total consumption.

Near maximum speed, manoeuvring is not easy because of the small excess thrust available, but with a boost rocket operating, relatively tight turns become possible. Fig. 14 shows the influence of rocket thrust on the radius of turn and on the duration.

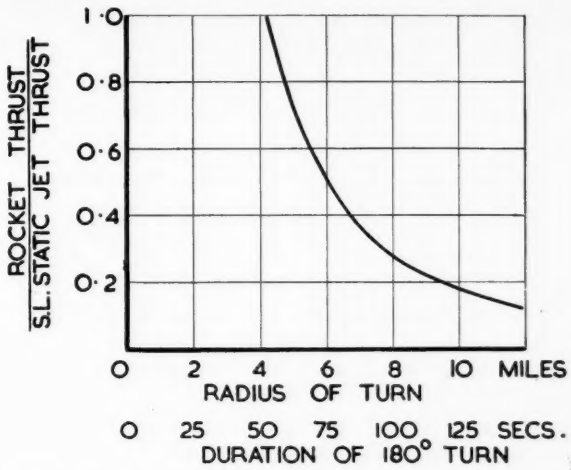


FIGURE 14. Influence of rocket thrust on manoeuvrability at 50,000 ft. and 900 m.p.h.

USE AS MAIN POWER PLANT

It will have been noticed that in all the uses discussed so far, performance depends upon the ratio of rocket thrust to main engine thrust. This can vary between the two limits of zero and 100 per cent. rocket thrust. In the latter case, we have the pure rocket-propelled aircraft of which the German Me163 and the American Bell X-1 were examples. The former was an interceptor fighter with a performance well ahead of any other contemporary aircraft and it illustrated the importance of new flight techniques to suit the new form of propulsion. The latter (Fig. 15) was purely a research aircraft but with its speed of over 1,200 m.p.h. and height of over 80,000 ft., it indicated what the future may have in store.

Both of these aircraft had a characteristically deep fuselage section in order to store the large propellant supplies required and both could be operated at reduced thrust for cruising in order to obtain an extended endurance. Although this enabled a longer time of operation, it did not extend the range greatly and it is interesting to see that much greater ranges can be obtained by a radically different flight plan. This consists in following a ballistic trajectory from the ground until all the propellant is used. By such time it may be assumed that the aircraft has reached very low pressure altitudes and the drag resistance is small. At the same time the aircraft has stored in it a great deal of energy, both kinetic and potential. This energy can be utilised to overcome drag, first by conversion of the kinetic energy and later by use of the potential energy. Furthermore, as all the propellant has been used, the aircraft weight will be relatively small and so will the drag.

As an example, the trajectory of a V.2 with wings would be as shown in Fig. 16. It would cover almost 600 miles in 20 minutes and would land at 90 miles per hour. This final subsonic glide and landing could be eased if a small turbo-jet engine of about 1,500 lb. thrust were installed. This would stretch the glide and enable the pilot to make a normal circuit and landing.

While an aircraft of V.2 size would not have a very large payload, there is no reason why much larger designs should not be made in which both propellant and payload are increased. Tsien, at California Institute of Technology, made a theoretical study of such an aircraft with a take-off weight of 50 tons and landing weight of 10 tons which would make the trans-American trip of 3,000 miles in under one hour. Sänger, in Germany, made a wartime study[4] of an even more ambitious aircraft which would fly halfway round the world in approximately $2\frac{1}{2}$ hours. This could be achieved by accelerating to a large enough velocity at the beginning of the ballistic trajectory. On re-entering the upper atmosphere after the dragless flight path, the lift force generated would be sufficient to turn the aircraft back on to a climbing path and the kinetic

FIGURE 15. Bell X-1 research aircraft powered by RM6000 (*see* Fig. 30)

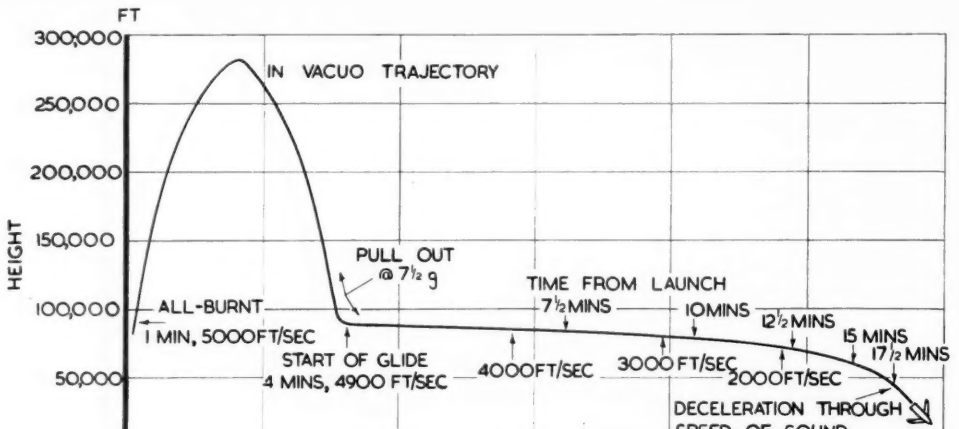


FIGURE 16. Typical trajectory of winged V.2.

energy would be re-converted into potential energy with only a small loss due to the drag suffered while the machine was in the atmosphere. The process would be repeated as the aircraft returned to the atmosphere again and a series of "bounces" into space would occur. In this way, the energy expended for a given flight distance would be greatly reduced because so much of the path would be in practically drag-free conditions.

Although Sänger's proposal involved many formidable aircraft and motor problems, none of these should be insoluble, and it again emphasises the advantages of an unorthodox flight plan. There can be no doubt that this technique of storing energy in the aircraft and making as much of the flight path as free of drag as possible, is where the future of the rocket motor as a main power plant must lie. In the meantime, there are many ways in which the rocket can be used in co-operation with other power plants. Just as the turbo-supercharger improved the performance of piston engines, the rocket can be made to improve the performance of turbo-jet engines or ram-jet engines.

Rocket Motor Problems

Many of the problems associated with rocket motors are similar to those of other propulsion units, but generally they arise in much more concentrated form. On the other hand, there are some problems which are peculiar to rockets alone and others which do not exist at all. To consider all the problems would entail much more space than is permissible in the present paper, and so the discussion will be confined to some of the more important ones, which have a direct bearing on the design and use of these engines.

As noted in the previous sections, motor weight and propellant consumption for unit thrust are of primary importance. These are influenced by numerous design factors such as permissible gas temperature, pressure, combustion efficiency, heat transfer, methods of pumping propellants, of ignition, cooling, thrust variation, and so on. Before examining these, it will be useful to consider the layout of the main components and their functions. It is not proposed to deal with solid propellant motors which are of relatively short endurance and only suitable in aircraft applications for assisted take-off, nor with liquid monopropellant forms which generally will be of lower performance than bi-propellant motors.

Figure 17 shows a diagrammatic layout of the bi-propellant type. Separate fuel and oxidant tanks are used and feed pipes lead from them to the respective high pressure pumps. The propellants are then delivered to the combustion chamber through some form of control valve. One component is led into a cooling jacket surrounding the chamber and thence to the burner head; the other goes directly to the burner head where both are injected in such a fashion that rapid mixing and combustion occur. The large volume of hot gas generated then expands through a convergent-divergent nozzle to give the characteristic supersonic rocket jet. An alternative to this arrangement is to omit the pumps and feed the propellants by pressurising the tanks with a suitable compressed gas. This method gives a lighter overall weight of motor for short durations, but for operating times of more than 30 to 60 seconds, depending upon the thrust, it is more economical to use a pumping system.

The pumps may be driven by a small gas turbine as in Fig. 17, or by mechanical connection with the main engine where this is employed. Fig. 18 shows the layout

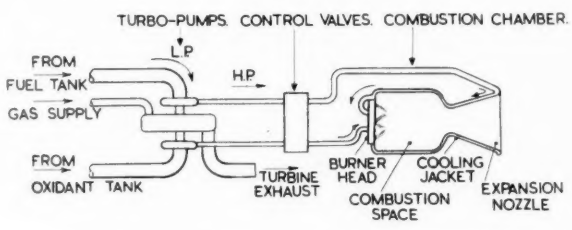


FIGURE 17. Diagrammatic layout of bi-propellant rocket motor.

of components in the Armstrong Siddeley Snarler, which was designed for the second arrangement. It can be seen from this figure that the components need only be connected to each other by propellant pipes and thus considerable flexibility in their relative positioning within an aircraft is possible.

SPECIFIC CONSUMPTION

There are two basic reasons for the high propellant consumption of the rocket motor. The first is the fundamental one that the oxidant required for combustion of the fuel is carried by the aircraft and not picked up in flight from the atmosphere. Thus, to provide equal heat energy the rocket must carry at least an additional weight of oxygen sufficient to burn the fuel. For a hydrocarbon fuel this is approximately three and a half times the weight of fuel and so the overall consumption must go up to at least four and a half times that of the equivalent air-swallowing engine. The second reason for high consumption is the inherently high jet velocity of the rocket. For a given available kinetic energy of the exhaust gas, the thrust produced varies inversely with the jet velocity which is almost four times as great as that of the turbo-jet engine. Combining these two factors gives consumptions of nearly eighteen times the turbo-jet figure and the question arises whether anything can be done to reduce this ratio.

An examination of the parameters will reveal the answer, but first it should be noted that it is more usual with rockets to consider specific impulse, which is the inverse of specific consumption. It is defined as the thrust produced with unit rate of propellant consumption and it can be written as

$$I = \frac{3{,}600}{q} = \frac{v}{g} = \sqrt{\left\{ \eta \frac{2}{g} \frac{\gamma}{\gamma - 1} \frac{KT_1}{M} \left(1 - \left(\frac{P_2}{P_1} \right)^{\frac{\gamma - 1}{\gamma}} \right) \right\}} \qquad (1)$$

In practical motors I lies between 200 and 250 lb./lb./sec. and improvements depend upon improving the parameters in the foregoing expression. T_1, M and γ are functions of the propellants used and their mixture ratio while the ratio P_1/P_2 is set by the designer. It is usually of the order of 20 : 1 or 30 : 1 and is the main factor determining the thermal efficiency. The more it is raised, the better the specific impulse becomes, but the rate of improvement falls off rapidly above 20 : 1 and even an infinite pressure ratio would only raise it by 50 per cent. Also the gains must be balanced against the disadvantages of increased nozzle weight, which will be referred to later.

The other possibilities for improvements appear on first sight to be an increase in gas temperature T_1 and a decrease in gas molecular weight M. These two factors are not, however, independent and the objective must be to make T_1/M an optimum. The variation of these parameters for a liquid/oxygen petrol propellant combination is shown against mixture ratio in Fig. 19. Because of dissociation the maximum gas temperature does not occur at stoichiometric mixture, but at some 10 per cent. fuel rich, beyond which it decreases slowly. Similarly, the molcular weight of the gas tends to fall with rich mixtures, but more rapidly, and the combined effect is to give a maximum of T_1/M at almost 40 per cent. rich. This is repeated in the specific impulse curve, although the gas temperature has fallen from 3,400°K. to 3,280°K. While this reduction in temperature is a fortunate accident for the designer who has to combat its effects on the combustion chamber walls, it still leaves it at values much higher than those found in any other internal combustion engine and the heat transfer problem is formidable. Thus, even if propellants with higher gas temperatures are available, they may have to wait for improved cooling techniques before they can be used.

A more attractive alternative is the reduction of molecular weight and this implies a fuel rich in hydrogen. Hydrazine (N_2H_4) and ammonia (NH_3) are good examples, but another consideration must enter at this stage. Not only must a high specific impulse per unit weight of propellant be achieved, but equally important is a high specific impulse per unit volume. The importance of this can be seen by the simple example given in Table III of the combustion of liquid oxygen and liquid hydrogen.

This shows that the fuel rich mixture has 15 per cent. advantage in performance on a weight basis, but is 20 per cent worse on a volume basis. For both mixtures

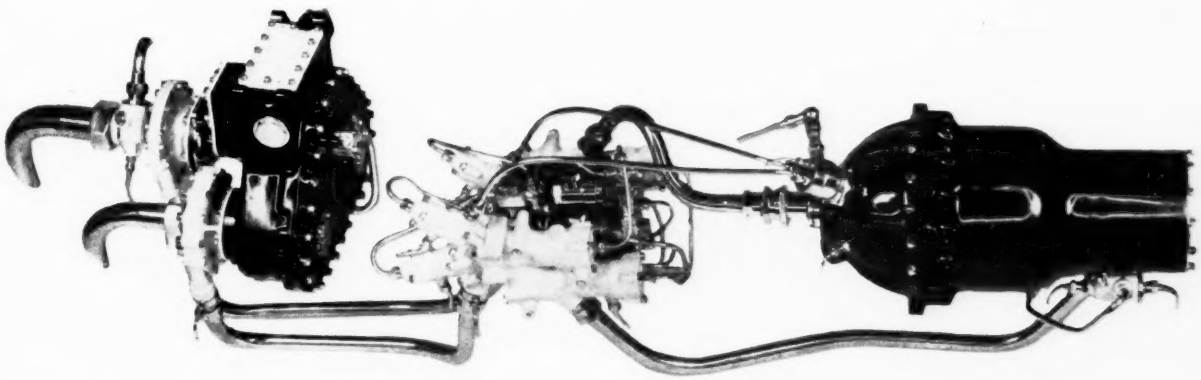


FIGURE 18. Armstrong Siddeley Snarler liquid oxygen/alcohol rocket motor with main engine drive for pumps.

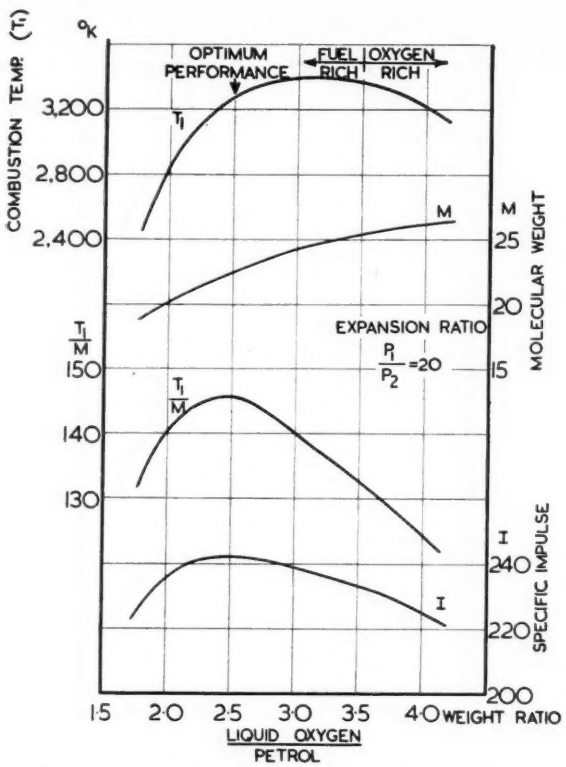


FIGURE 19. Effect of mixture ratio on rocket propellant performance.

the weight specific impulse is much greater than for the average propellants, but the low density of liquid hydrogen results in a poor volume specific impulse. By comparison, the liquid oxygen/petrol impulse is approximately 2,370 lb./gall./sec., nitric acid/hydrocarbon 2,780 lb./gall./sec., and 85 per cent. hydrogen peroxide/hydrocarbon 2,760 lb./gall./sec.

The three oxidants mentioned are those in most common use, and much controversy has raged round their respective merits and faults. Cleaver[2] discussed them in detail and there is little to add to his review, except to note that on a volume basis nitric acid and hydrogen peroxide are practically equal, but the latter has a combustion temperature of only 2,600°K. compared with 2,950°K. for nitric acid and nearly 3,300°K. for liquid oxygen. For this reason alone, hydrogen peroxide must be very attractive to rocket motor designers and when coupled with its ability to provide energy directly for driving the turbo-pumps and accessories, it becomes, in the author's view, pre-eminent.

TABLE III

PERFORMANCE OF LIQUID OXYGEN AND LIQUID HYDROGEN

Mixture	*Stoichiometric*	100% *Fuel rich*
Oxygen/Hydrogen by weight	8 : 1	4 : 1
Combustion temperature T_1 °K	3,525	3,025
Gas molecular weight M	15·5	9·8
T_1/M	227	309
Specific impulse lb./lb./sec.	306	353
Propellant mixture density lb./cu. ft.	25·5	17·6
Specific impulse lb./gall./sec.	1,250	1,000

The remaining factor in the specific impulse equation is the efficiency η with which the propellant chemical energy is converted into gas kinetic energy. It corrects the theoretical impulse to practical values, taking into account combustion efficiency, heat transfer losses, imperfect gases, friction losses and other expansion nozzle losses. These can account for some 5-10 per cent. reduction in impulse and any improvement must be mainly a matter of improved mechanical design.

It can now be seen that the answer to the question of improving specific consumption is that the prospects are not very bright for any major reduction, but a number of minor reductions may be possible. These should not be neglected as they can give a more than proportionate improvement in performance. In a ballistic flight path, for example, the range varies as the square of the specific impulse so that a 10 per cent. improvement in impulse will give 21 per cent. increase in range.

While the improvements to be expected by changing the propellants or modifying the motor design are limited, one further possibility exists. The use of an air augmentor duct surrounding the rocket jet would give an increase in thrust due to the interchange of rocket jet kinetic energy and momentum with those of air in the duct. Theoretically this increase depends upon the augmentor duct and rocket jet mass flow ratio. It falls to zero as forward speed/rocket jet velocity increases and then once more rises. As an example, for a typical arrangement with a mass ratio of 10 : 1, thrust increase would be 40 per cent. at take-off, zero at 450 m.p.h. and 5 per cent. at 1,000 m.p.h. To achieve this, the entry to the air duct would have to be shaped as an accelerating or diffusing section according to the speed ratio. This is, of course, similar to the intake problem facing the turbo-jet and the ram-jet. Practically, the amount of augmentation depends upon the friction losses, mixing rates and entry efficiency. In some experiments with a small rocket motor, made at the College of Aeronautics, Cranfield, ducts with augmentor/rocket jet diameter ratios from 7 : 1 to 14 : 1 were tested statically, and thrust augmentation from 17 per cent. to 40 per cent. was actually measured. In all cases the optimum length/diameter ratio of the duct was between 5 and 7. Duct dimensions are important and too large a duct would be difficult to install, apart from the excessive

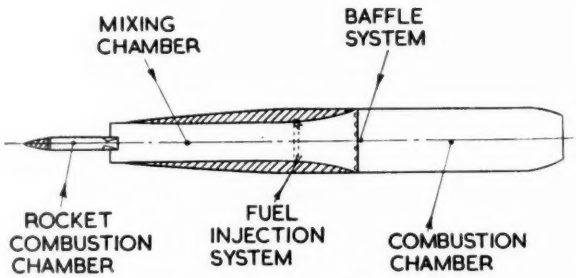


FIGURE 20. Rocket-ram-jet duct combination.

TABLE IV

ROCKET MOTOR WEIGHTS

Motor	*Oxidant*	*Thrust lb.*	*Weight/thrust*
BMW.109-718	HNO_3	2,750	0·065
V.2	LO_2	60,000	0·035
A.S.M. Snarler	LO_2	2,000	0·107
RM6000-4c	LO_2	6,000	0·035
HWK.109-509	H_2O_2	3,750	0·100

friction and drag losses introduced. These are likely to be large in any case for high speed flight and, as altitude increases, the air mass flow will be reduced and the proportionate thrust increase will be less. Thus the advantage of a simple augmenting device will mainly apply to the low speed, low altitude range, that is, to take-off. For this purpose it need be only a light tube as pressures and temperatures will not be far removed from atmospheric. It can be easily jettisoned after take-off, either by itself or with the rocket motor.

The rocket-duct combination was studied by the Germans, not primarily to improve the rocket performance, but to assist ram-jets at low speeds[5]. Fig. 20 shows one of the arrangements adopted. It was effectively a ducted rocket coupled to a ram-jet combustion chamber. With it ram-jet static thrust could be developed, although very inefficiently. Its chief merit was that the rocket jet was of decomposed hydrogen peroxide and the oxygen present enriched the ram-jet air supply.

MOTOR WEIGHT

It has already been indicated that the rocket motor is very light at sea level and, relative to other engines, much lighter as the altitude increases. Some actual weights are given in Table IV. These show considerable scatter in specific weight, but the general indication is that figures of 0·05 lb./lb. or less should be possible at the present time. Actual figures will depend upon designed combustion pressure as an increase in pressure will involve heavier gauge material in all pipes, control valves, pumps, and the combustion chamber itself.

The weight of the motor may be written as

$$W_m = a + b \,.\, F \quad . \quad . \quad . \quad (2)$$

and the weight of propellant

$$W_p = q \,.\, Ft. \quad . \quad . \quad . \quad (3)$$

The relative overall weight for a motor operating at pressures P_1 and P_2 can then be written

$$\frac{W_1}{W_2} = \frac{a + b_1 F + q_1 Ft}{a + b_2 F + q_2 Ft} \quad . \quad . \quad (4)$$

An analysis on these lines will give results of the form shown in Fig. 21. It might have been assumed that all the main components would increase in weight with increasing pressure, but actually the combustion chamber dimensions are reduced and its weight falls. Other advantages follow from this, but these will be discussed in a later section. The reduction is offset by the extra length of divergent nozzle necessary to obtain complete expansion of the gases, but the nozzle effect only begins to take charge at comparatively high pressures, say 700 lb./in.² and above, assuming expansion to 14·7 lb./in.². The result is that the total motor weight shows a shallow minimum near 300 lb./in.² combustion pressure (Fig. 21(*a*)). Against that, combustion chamber propellant consumption is continually reduced as pressure ratio increases, but consumption by the turbine driving the propellant pumps increases (Fig. 21(*b*)). The latter is a small fraction of the main consumption, being between 1½ per cent. and 3½ per cent. at 300 lb./in.² chamber pressure, depending upon the design efficiency. The rate of increase at high pressures will, however, more than balance the decrease of main consumption and the total consumption will tend to rise slowly. Finally, a combination of the fixed motor weight and the propellant weight which is variable with time will give an all-up weight at a fixed combustion pressure which can be plotted against operating time (Fig. 21(*c*)). By comparing various constant pressure conditions, the optimum can be found. It might be assumed that this would be at the pressure which gave the minimum total consumption rate as, by operating long enough, this would more than balance any extra motor weight. While this is true, the time at which an advantage would be realised would involve much greater quantities of propellant and longer operating times than are normally possible. In practice, the advantages in going higher than 600 lb./in.² is small and other considerations tend to keep it lower.

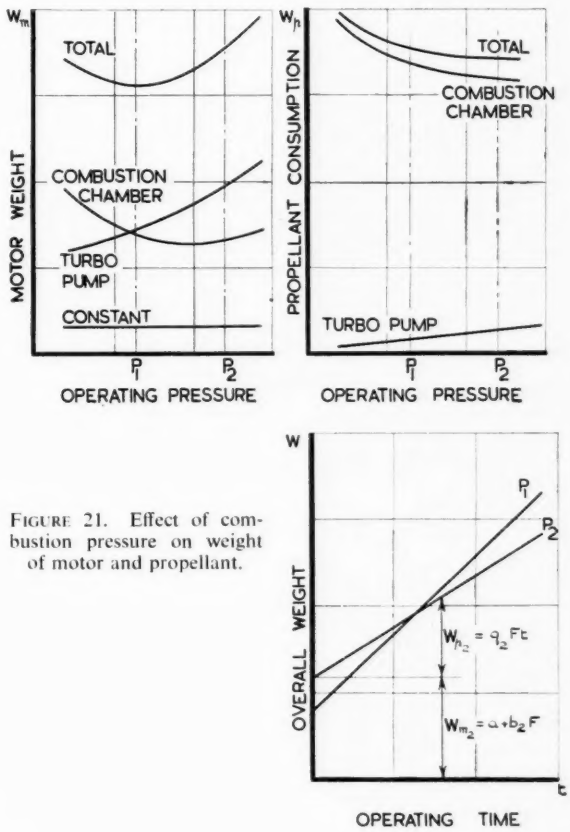


FIGURE 21. Effect of combustion pressure on weight of motor and propellant.

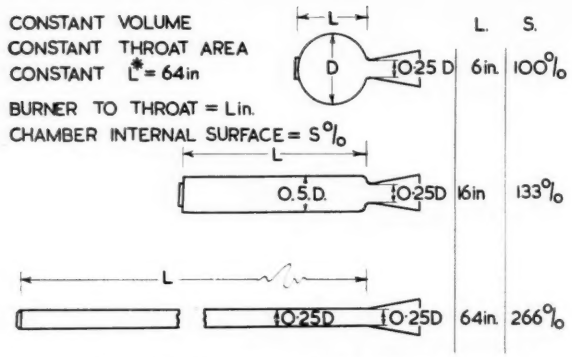


FIGURE 22. Combustion chamber shapes.

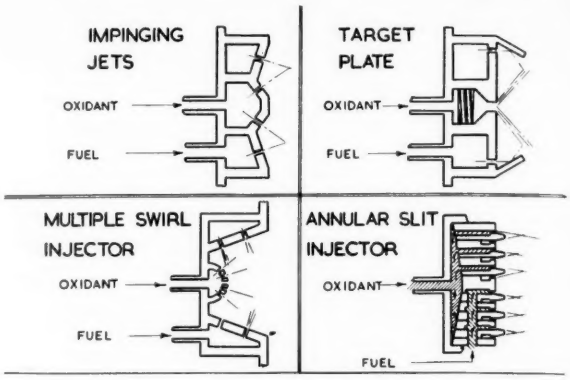


FIGURE 24. Burner head arrangements.

If it is assumed, for example, that the motor will be used to boost the aircraft performance on climb, or in high speed acceleration, it is unlikely to be used below 20,000 ft. At this height the atmospheric pressure is less than half the sea level figure and consequently a combustion chamber pressure of 300 lb./in.^{2} abs. which would give an expansion ratio P_1/P_2 of 20:1 at sea level, could give, with a suitable nozzle, more than 40:1 at 20,000 ft., or 66 : 1 at 30,000 ft. This would result in a motor weight W_m only slightly greater than the normal 20 : 1 design, but would give a propellant consumption W_p even better than indicated for the corresponding high pressure design.

Combustion Chamber Design

Following the discussion on component weights and the influence of combustion chamber pressure, it may be desirable to examine their design in more detail. The combustion chamber consists of a burner head, combustion space and exhaust nozzle, and associated with it are an ignition system, a cooling system and a thrust control system.

Generally, the heat release from unit volume of combustion chamber is much greater than for the air-swallowing engines and even when measured as an intensity it is much superior. This is due, in part, to the high pressures and temperatures in the chamber which encourage high reaction rates and, in part, due to the burner head and chamber design which ensures good mixing of oxidant and fuel and the longest "time of stay" for reaction.

Many shapes and sizes of chamber have been tried and an equally large variety of propellant injectors. For a given chamber volume V_c, a spherical shape has the advantage of minimum surface area exposed for gas heat transfer and the strongest mechanical design. The German 509 A.2 chamber approached this shape, but involved some difficult production problems. At the other extreme, a long tubular chamber ensures that the propellant cannot pass through without a relatively long residence time. It gives a small cross section, but the gas velocity will be greater and the chamber wall surface will be large. These variations are shown diagrammatically in Fig. 22 which gives two extreme examples and one intermediate. In all cases the combustion volume is the same and the divergent nozzle is the same. It follows that the average time of stay is the same, and this can be conveniently described by the characteristic length L^* of the chambers. This is defined as

$$L^* = \frac{V_c}{A_t}.$$

In the third example, the so-called "throatless" chamber, the combustion space has the same diameter as the throat and so its length is L^*. Experiment has shown that normal combustion chambers are satisfactory when L^* is not less than 50-70 in., depending upon the burner design and the propellants used. It has been found, however, that the throatless chambers can be run successfully at very much smaller L^* values (12 in. or less) and this suggests that the direct path length may have some influence, especially as the combustion efficiency of spherical chambers is not high unless L^* is large. If this is so, considerable reduction in conventional chamber size could be achieved.

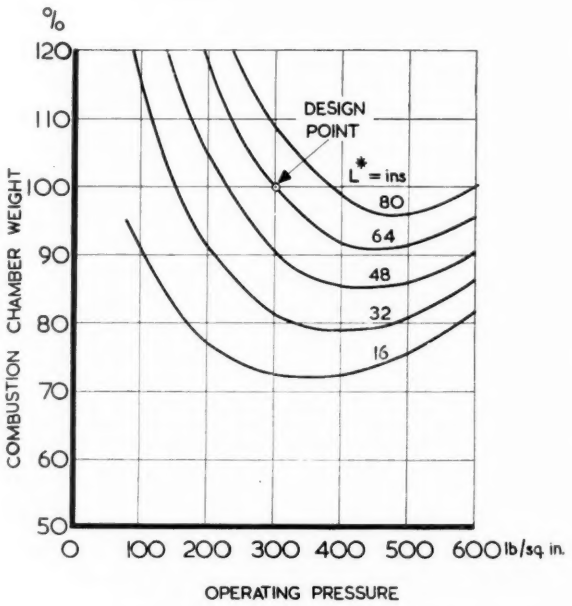


FIGURE 23. Effect of L^* on combustion chamber weight.

The advantage of reducing the L^* is that weight is reduced and this is shown by the curves in Fig. 23 which have the same form as in Fig. 21(*a*). In addition, the wall surface for heat transfer is less, but there is a fundamental loss in performance in small diameter tubular chambers, because the high gas velocity in the chamber entails a high pressure drop. It amounts to a loss of 21 per cent. in thrust for the throatless, compared with the spherical chamber, with the same initial pressure, but rapidly falls as chamber/throat diameter ratio increases and it is only $1\frac{1}{2}$ per cent. for the intermediate chamber. In this case the actual chamber length is assumed to be 16 in. and $L^* = 64$ in., but if the chamber length could be reduced to 12 in., L^* would drop to 48 in.

Other drawbacks of the throatless chamber are the small space available for the burner head and a tendency to unstable combustion when operating away from designed conditions. The latter is something akin to screech in turbo-jet reheat systems (*see* Ref. 6) and just as destructive. It can occur in any combustion chamber if appropriate conditions exist. These are not well understood as yet, but are related to the chamber design, propellant injections and fuel feed system. Theoretical studies have been made by Crocco[7] and others based on the assumption of a time lag between liquid injection and the development of gas pressure by combustion. In chambers of small characteristic length, this lag can represent a large proportion of the total time of stay and conditions are then particularly conducive to building up and maintaining large amplitude pressure fluctuations.

BURNER HEAD

The burner head usually consists of a number of propellant injectors and its duty is to ensure the intimate mixing of oxidant and fuel in correct proportions as rapidly as possible. This is the first of the complex series of processes which the propellants undergo. Almost simultaneously atomising, vaporising, mixing and partial combustion are proceeding, but knowledge of the best conditions and how to produce them is slight, as is witnessed by the widely different examples of burner shown in Fig. 24. One point which is fairly clear is the need to keep the axial velocity of the propellants low when injected. Reference has been made to the burner-to-throat distance and a high axial velocity would tend to reduce the effective length of this. The requirement for low injection velocities calls for a relatively large injection area to deal with the high flow rates and this means that burner heads will have difficulty in matching the demand for small diameter chambers. It must also be remembered that the burner head has a load of 300 lb./in.^{2} or more, according to the combustion pressure acting over its face and must not be seriously weakened by too many or too large injector holes.

EXPANSION NOZZLE

This component is almost of equal importance with the combustion chamber proper because its weight may be more than 50 per cent. of the combined weight and its efficiency decides how much of the gas pressure energy developed in the chamber is converted to kinetic energy. As frequently happens, the two factors are mutually opposed and a compromise is necessary. Practical nozzles are usually made as straight sided truncated cones to ease production, but a better theoretical contour can be found which gives a relatively short nozzle. If the conical nozzle is shortened by increasing its angle, there is an increasing thrust loss due to the radial component of the jet. This amounts to about 3 per cent. when the cone angle is 40°, but greater divergence produces a rapidly increasing loss as shown in Fig. 25. The figure also indicates how the nozzle relative weight decreases with increasing divergence and increases with increasing pressure ratio for a fixed combustion pressure. The advantage of designing for a high pressure ratio and a low exhaust pressure has been mentioned already, but again the extra nozzle weight must be balanced against reduced specific consumption. This is not entirely dependent upon designed pressure ratio as the thrust will be increased for an under-expanded jet by an amount proportional to the excess pressure remaining in the jet and the exit area of the nozzle. The total will be less than that for a correctly expanded jet, but the loss is not serious within a reasonable range of exhaust pressure either side of correct. This is shown in Fig. 26 where the specific impulse is plotted against altitude for correct expansion at all altitudes, at sea level only, and at

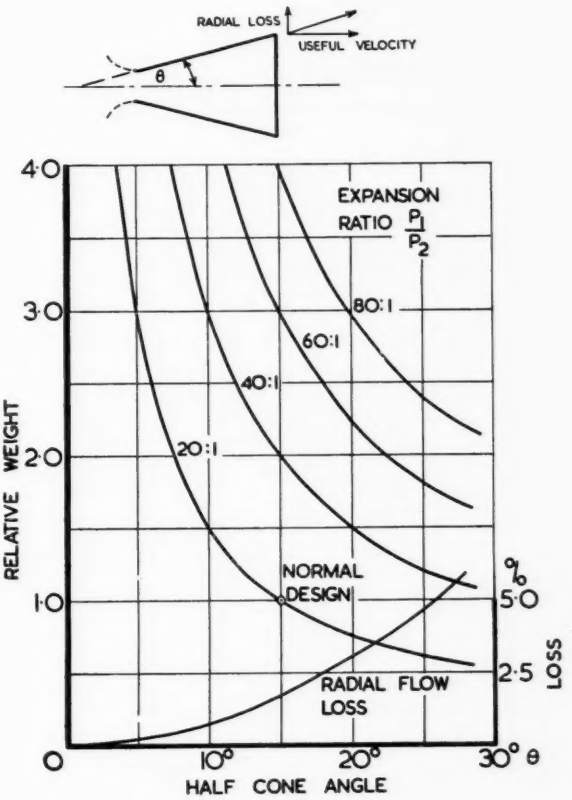


FIGURE 25. Expansion nozzle design.

20,000 ft. only. In all cases the combustion chamber pressure is fixed at 300 lb./in.^{2}. The last case shows an inferior performance near ground level, but above 30,000 ft. is giving a considerable saving in consumption. For a motor of 5,000 lb. thrust it would amount to 0·75 lb./sec. at 50,000 ft. for a probable increase in nozzle weight of 15 lb.

Although this would appear to give a worthwhile improvement, it does involve a longer and larger diameter nozzle. This may not be a serious matter in an aircraft installation, but a real problem could be introduced in the cooling of the extra nozzle surface if the heat transfer is already critical.

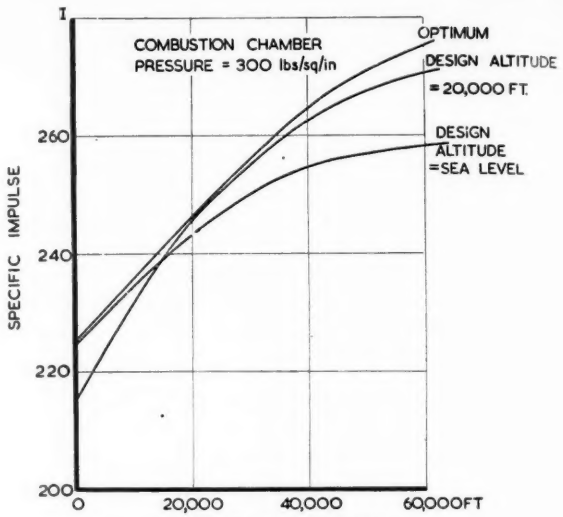


FIGURE 26. Effect of expansion nozzle design on performance.

COMBUSTION CHAMBER COOLING

No discussion on rocket motor problems would be complete without some reference to the heat transfer difficulties that beset the designer. The combustion chamber contains gas at very high temperatures which is flowing at high velocities. These conditions produce high rates of heat transfer to the chamber walls and it is essential for the walls to get rid of the heat picked up just as rapidly, or else their temperature will rise to the point of failure. The usual method of doing this is to transfer the heat to the liquid propellant which flows in a jacket surrounding the chamber before being injected through the burner head. This has the advantage that very little heat is actually lost, as the flow out of the chamber is absorbed by the propellant and then returned to the combustion space. Because of this, it is important that the total heat transferred should not be more than the propellant is capable of absorbing without boiling. The total quantity will depend upon the surface area exposed to the gases and this should be kept to a minimum. In relation to the thrust, surface area increases as the thrust decreases and a point will be reached where regenerative cooling cannot be maintained. In present day motors this is at a relatively low thrust, but if combustion temperatures are raised, so will be the minimum size of chamber. For a given thrust, spherical chambers have the least exposed surface and for all chambers, the area is reduced by operating at higher pressures.

Some typical curves indicating the order of the temperatures to be expected at various sections of a chamber are shown in Fig. 27. It will be noted that the wall temperature on the gas side reaches values approaching 1,000°C. at the nozzle throat. This is very close to the limit of the material strength so that for higher gas temperatures some improvements are necessary. As the temperatures depend largely upon the convective heat transfer coefficients between the gas and wall and between wall and liquid, modifications to these coefficients would be one line of attack on the problem.

A small coefficient is required between the gas and wall in order to produce a steep temperature gradient across the boundary layer. There is little that can be done here except to introduce an artificial boundary layer of cool gas. This can be done by allowing a liquid film to flow on to the chamber wall. The liquid vaporises and its latent heat helps to keep the wall temperature down. The vapour will continue to keep the temperature low for a short distance downstream, but it will be quickly absorbed into the turbulent boundary layer and then becomes ineffective. Some method of avoiding this and injecting only boundary layer quantities could provide a big advance in rocket performance. At the moment, application of this film cooling technique is expensive in liquid consumption, as a fresh injection must be made at intervals through the chamber and each injection puts in many times the theoretical amount required. Consequently, as in early turbine blade cooling tests, the gain in performance is offset by the additional coolant expended.

On the other side of the chamber wall, the effort is towards obtaining a high heat transfer and this demands a high velocity of the coolant. This means a small radial passage width and a high pressure drop through the jacket. The latter is objectionable because of the extra pumping power required, but more so because the propellant must be at a higher pressure than the gases inside and hence the chamber is subjected to a collapsing load. This can be resisted by increasing the wall thickness, but this increases the resistance to heat flow and puts up the wall temperature on the gas side. The effect of wall thickness and passage width at a typical chamber section is shown in Fig. 28. Apart from the high pressure drop in the jacket, small coolant passage width presents a practical problem of assembling and holding the gap exactly right.

One method of improving the heat transfer on the liquid side is by nucleate boiling[8]. A large increase in heat transfer can occur without much rise in temperature if the liquid boundary layer boils and forms small bubbles which are swept off the wall into the main mass of the coolant. It is a difficult condition to design for and the danger is that the bubbles may coalesce and prevent liquid from reaching the wall. In this case failure would follow very rapidly. Probably very few chambers have been designed for nucleate boiling heat

transfer up to the present, but it may have occurred quite fortuitously in very many others. When it can be properly controlled it will assist the designer to improve the motor performance materially. If, for example, the heat conductance of the liquid film could be doubled, the wall temperature on the gas side at the throat in Fig. 27 could be dropped by about 80°C. or, alternatively, keeping the inside wall temperature the same, the gas temperature could be raised from 2,500°C. to 2,750°C. The same effect is obtained if the physical properties of the coolant are suitable. Water is one of the best coolants available, having a conductance twice as good as methanol and four and a half times better than kerosine at atmospheric temperature. In all cases, the conductance improves with increasing temperature and for kerosine is about 1·6 times as great at 100°C. as at 20°C. and for water, about 2·0.

The material of the wall influences temperature in the same way, a high conductivity giving a lower temperature if other conditions remain the same. This is also shown in Fig. 28, which includes curves for an aluminium alloy, heat resisting steel, and mild steel. Aluminium has a much lower temperature than the steels but, unfortunately, its specific strength (proof stress/density) is negligible at the temperatures required. Copper is even better than aluminium in easing heat transfer and wall thickness is not a major problem, but again its strength is low and it is susceptible to oxidation and erosion on the gas side. At the other end of the scale, heat resisting steels have the highest specific strengths at high temperatures, but their poorer conductivity causes higher wall temperatures which counterbalance the better strength. On the whole, therefore, mild steel proves to be as good a material as any.

Rocket Motor Control

Rocket control is a matter of major importance which is dependent upon factors such as the operational role of the motor, thrust range required, and operating altitude. The problems associated with it can be classified broadly under the following three headings:—

(*i*) propellant supply,
(*ii*) starting,
(*iii*) thrust control.

PROPELLANT SUPPLY

In all operations it is necessary to supply the propellants to the combustion chamber at a pressure which

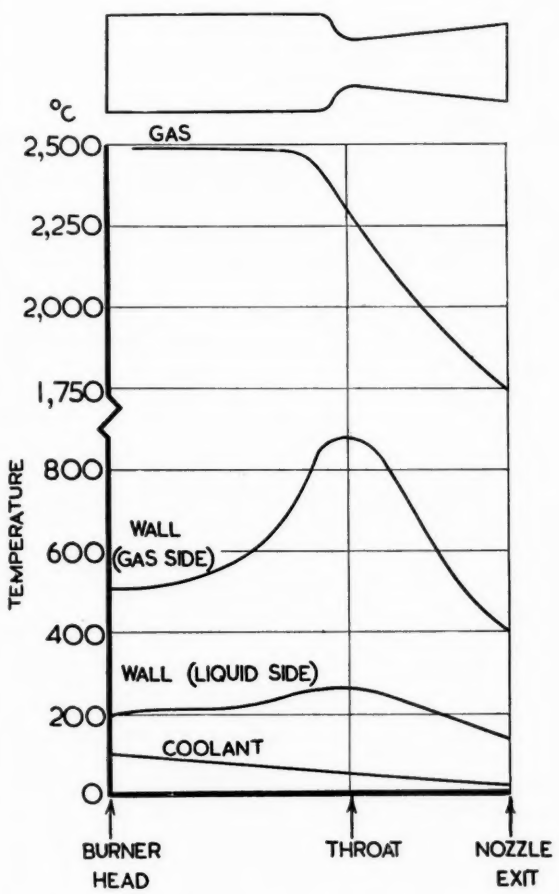


FIGURE 27. Typical combustion chamber temperatures.

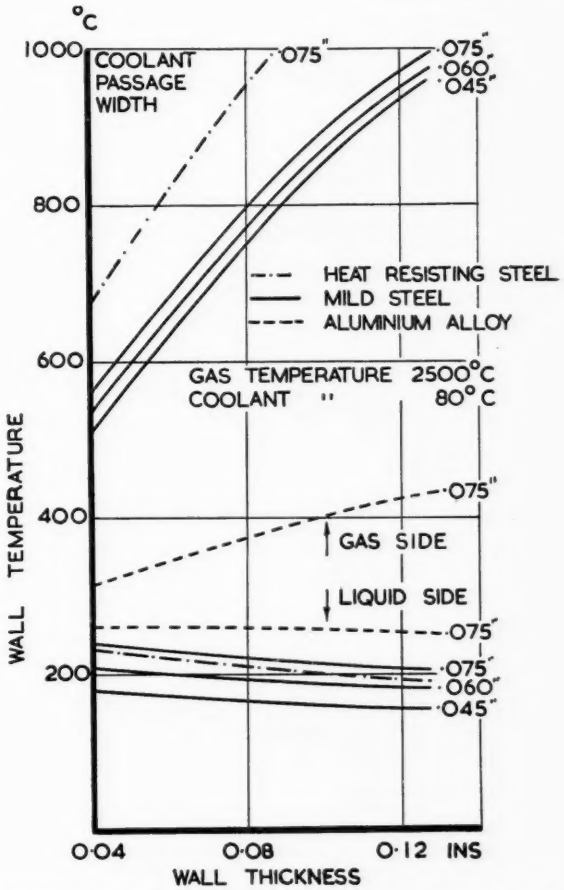


FIGURE 28. Effect of combustion chamber wall thickness, material, and coolant gap on temperature.

is high enough to ensure that they are injected against the combustion back pressure at an adequate rate. There are, in addition, various feed pipe, control valve and cooling jacket losses to be made good. The total delivery pressure may, therefore, be of the order of 450-750 lb./in.^{2}, and the flow about 2 gall./sec. for a 5,000 lb. thrust motor. To meet such requirements, the high speed centrifugal pump is the most compact unit and it has been universally adopted. The most appropriate drive for it is a small gas turbine rotating at the same speed. In this way the turbine and pumps can be mounted on the same shaft as was done by the Germans in the Walter 509 A.2 motor[9] and the rotating assembly weight kept to a minimum to assist rapid acceleration to full speed. In such a scheme, it is important to ensure satisfactory liquid seals which will prevent oxidant and fuel coming into contact in any fashion, bearings which will operate at high speed with the minimum of lubrication, and insulation of the propellants from the turbine heat.

The shaft power to drive the pumps will be of the order of 100 h.p. for a 5,000 lb. thrust motor and if this is turned into terms of propellant required to provide gas for the turbine, it may amount to 1·0 lb./sec., depending upon the turbine efficiency and available gas energy. This consumption is additional to the main combustion chamber consumption and will reduce the effective specific impulse of the motor. Because of this, there is a case for driving the pumps from the main turbo-jet engine when this is fitted. Generally such an arrangement will involve a gear box and clutch and, if operated at high altitude, will demand an appreciable proportion of the main engine power. In extreme cases it will limit the operating altitude and in every case it will add some permanent weight which will, of course, be compensated by the reduction in rocket consumption.

If the completely independent arrangement is adopted, the provision of turbine gas can be by decomposition of a monopropellant such as hydrogen peroxide or propyl nitrate, as used for gas turbine starters, or by combustion of the main propellants in a mixture giving lower temperature gas than the main combustion. The former was used on the Walter 509 A.2, some of the hydrogen peroxide provided for the main chamber being diverted through a catalyst chamber to the turbine. Such arrangements are shown diagrammatically in Fig. 29. The main problem in all cases is that of starting the pumps. It is possible to start a hydrogen peroxide system by the gravity head of a small propellant tank feeding steam to the turbine, but this is slow and either a compressed air drive to the turbine or small auxiliary pressurised propellant tanks feeding the gas generator is better. In these arrangements, the fitting of non-return valves will enable a tapping from the main propellant to be used once the pumps have run up to a working pressure.

The remainder of the propellant system consists of valves and interlocks which ensure the safe starting, thrust control and stopping. It should include a system for pressurising the main propellant tanks lightly to avoid cavitation in the pump inlets.

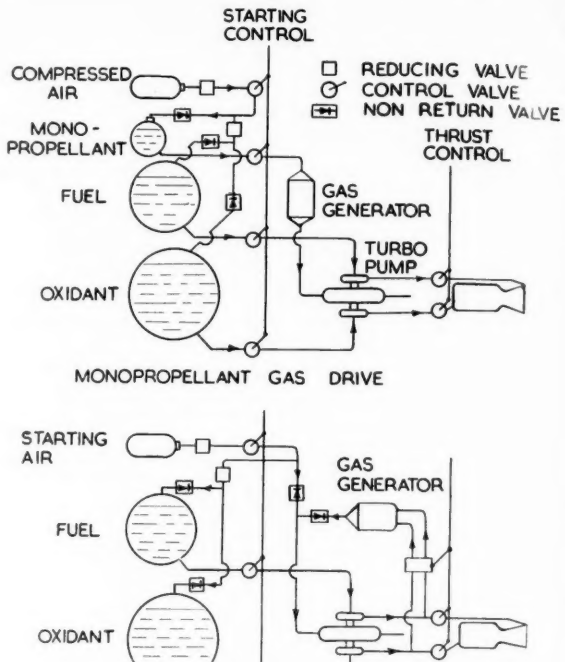


FIGURE 29. Diagram of turbo-pump drive systems.

STARTING

Starting a liquid propellant rocket motor is the most critical feature in its operation. This is primarily due to the high flow rates prevailing, which will cause a "hard" start if ignition is delayed even a fraction of a second. This can be illustrated by considering the combustion chamber of the 5,000 lb. thrust motor previously referred to. The combustion of 0·1 lb. of propellant would raise the pressure in the chamber to 360 lb./in.^{2}. Under normal operating conditions, this quantity would be injected in 0·0045 sec., but at the start, with no combustion back pressure, it would collect in only 0·0025 sec. If more propellant than this were allowed to collect before combustion, the pressure might be raised dangerously. It is necessary, therefore, to prevent an excessive amount of propellant collecting before ignition, or to ensure that there is no ignition delay. The former requires a reduction in starting flow rates or some method of purging liquids which collect in the chamber, and the latter some form of ignition which provides sufficient energy to produce immediate reaction of the full flow of propellants.

Reducing the flow rate can be accomplished by providing two or more sets of injectors in the burner head, each being separately controlled. One set can be used for starting and the others brought in successively as combustion is established. This is quite effective provided that the combustion resulting from the first stage does not develop too low a pressure. High pressure conditions are needed for satisfactory burning because

of the small combustion space available, and at pressures below about 60 lb./in.^{2} very rough burning may occur. This method involves some complication in the burner head design to enable separate stage feeds to be used. It was used successfully in the Walter 509 A.2 motor, which also incorporated a blast of decomposed hydrogen peroxide to sweep any accumulation of liquid out of the chamber before ignition. This is one of the advantages of hydrogen peroxide, but the same effect could be obtained with liquid oxygen by application of a little heat. In other cases, a permanent gas might be used.

The second method may be regarded as an extension of the first. The combustion produced by the first stage low flow is replaced by some other source of heat energy, such as a solid propellant cartridge or a pilot flame. For repeated use, as required in aircraft, the pilot flame appears attractive. This is produced in a small pilot combustion chamber built on to the burner head so that the hot gas rushes into the main chamber, supplying enough heat to raise the main propellant flow to a temperature at which rapid reaction is initiated. At the same time it can act as a purge of any liquids which fail to vaporise or react immediately. Such a system transfers the initial ignition problem to a smaller scale where there is much less difficulty in obtaining reliable ignition by high energy spark or similar arrangement.

The initial energy for reaction may come from the propellants themselves if suitably selected. Hydrazine hydrate and hydrogen peroxide, aniline and nitric acid, zinc di-ethyl and oxygen are all self-igniting pairs and others can be used. In these cases, impingement of the two liquids starts an exothermic reaction in the liquid phase which raises the temperature until vapour is formed. Reaction continues in the vapour phase until the ignition temperature is reached and combustion begins. The advantage of this is that no special ignition equipment is required, but the disadvantage is that the pre-ignition reaction is slow and in some conditions will give "hard" starts. At low temperatures, the ignition delay increases, but more serious is the increase in delay with reduction in pressure until, ultimately, ignition will not occur at all. This limit appears to be similar to the normal inflammability or ignition limits experienced with gaseous combustible mixtures at low pressure. Consequently, the use of self-igniting liquids will be unsatisfactory if ignition is required at high altitude. A further objection to self-igniting propellants is the risk of fire if an accidental leak occurs. This was claimed by the Germans as an advantage as the leak became evident immediately, whereas with other propellants an explosive mixture might form which could remain undetected until a catastrophic explosion occurred. The answer is, of course, to ensure that no such leaks occur.

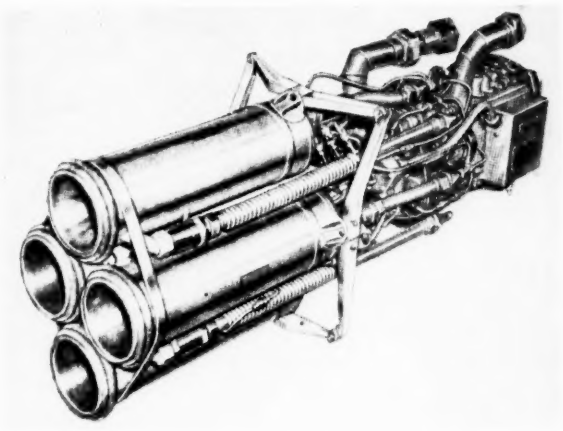


FIGURE 30. Reaction Motors RM6000-4c rocket motor with four combustion chambers.

Another aspect of starting is that of pumping the propellants. If the pumps are driven from a main turbine engine, it is only a matter of operating a clutch, but if an independent turbine drive is used, some arrangement such as suggested in the last section is necessary. In all cases a sequence of events occurs during starting and the control system should be such that no action can occur until the previous action has been completed satisfactorily. Thus, no igniter should operate until the pumps are giving the starting pressure, no propellant should flow until the igniter is working, no main flow should be possible until the first stage or pilot chamber is operating satisfactorily, and so on.

THRUST CONTROL

The first question that arises is to what extent variable thrust is required with rocket propulsion. Generally, the objective is to obtain the maximum thrust additional to that of the main engine during some special manoeuvre. In such cases, it is unlikely that the pilot will require anything except full or zero thrust from his rocket motor. On the other hand, the ability to select any intermediate thrust gives greater flexibility in controlling such aircraft and is almost a necessity in cases where the rocket is the major power plant and the aircraft is used in a relatively conventional manner.

Thrust variation may be continuous or in steps. The latter is more simple and can be carried out with a single combustion chamber or by using a number of chambers in combination. Two chambers giving thrusts in ratio 2 : 1 could be used, each operating at full thrust, to give thrust steps of 1, 2, 3 and by using more chambers a greater thrust range could be obtained. The motor for the Bell X-1 aircraft was of this type, but had four identical chambers as shown in Fig. 30. The motor for the German Me 163 had two chambers but the larger had an almost continuous thrust variation from 100 per cent. to 15 per cent. This was achieved by using three sets of injectors, each of which could be cut out in succession and each of which had a range of flow. This large variation produced a change in combustion pressure from 300 lb./in.^{2} to 50 lb./in.^{2}, but combustion at the lower figure was rough and inefficient. Also, with an expansion nozzle designed for 20 : 1, the throttled condition gives a very over-expanded jet near sea level, but at a suitable altitude the nozzle would be giving correct conditions once more.

It can be seen that from the combustion chamber end, there is no difficulty about producing variable thrust and all that is involved is a throttle or series of shut-off cocks to regulate the propellant flow. This

may not be quite so simple as the statement implies, as a number of separate feed pipes will be involved and it is desirable to keep the oxidant/fuel mixture ratio constant during the throttling. From the pumping end, no special problems arise with the mechanically-driven pumps as a simple throttling of the propellant supply will ensure the delivery of the correct quantity at the appropriate pressure. With the turbo-pump system, rather more care is necessary to match the pump deliveries and pressures with chamber requirements in order to reduce the turbine consumption. A control valve is necessary to meter the propellants required for the gas to drive the turbine. This may take the form of a throttle in the turbine feed line which is set according to the equilibrium condition required. If, however, a slight disturbance occurs to the feed pressure, the turbine speed will alter and there will be a consequential change in thrust. Equally, a change in turbine back pressure would have the same effect. This would be particularly noticeable during a climb and some form of automatic adjustment of the throttle will be necessary. One method could be by means of a signal from the pump pressure operating against a datum set by the pilot's throttle. In addition, some form of over-speed governor is required to guard against sudden removal of the load such as might occur if the pumps run dry.

Conclusion

It is obvious that rocket propulsion for aircraft is a very specialised field and that its main applications in the near future will be as an adjunct to other power plants. In the role of a thrust booster for short periods, it can enhance the performance of the air-swallowing engines enormously over the whole speed and altitude range. Its value is primarily in military aviation, but applications like assisted take-off can have advantages for civil aircraft.

At the beginning of the paper it was suggested that, relatively, the rocket power plant is in its infancy. With this in mind, it is possible to anticipate considerable development in the years ahead and to foresee in the not too distant future a reversal of its present subservient position. It will become the main power plant of special purpose long-range aircraft, supported by small turbo-jets which will be used merely for landing purposes. This will be one of the first steps into the region where there can be no question of the rocket's supremacy. When this occurs, it is almost certain that it will not be long before the rocket will open the doorway for humanity to extend its dominion into interplanetary space.

Before this comes to pass, there are many problems to be solved. Even partial solutions of these will improve motor performance for earthbound uses greatly. At present there are relatively small expectations of improvement in specific fuel consumption, great need for better heat transfer and motor cooling, and good hopes of reduction in motor specific weight.

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DISCUSSION

M. J. BRENNAN (Chief Designer, Saunders-Roe, Ltd., *Fellow*): He was in almost complete agreement with everything Professor Baxter had said. He had been specially interested in the latter part of the lecture where Professor Baxter showed how very straightforward a business it was to make a rocket engine.

One of the Figures where the rocket was shown at 80,000 feet, was apparently an air-launched rocket aircraft; in fact they might generalise and say it was a composite aircraft. It was taken up by some sort of internal combustion engine, air-swallowing, and then went under its own rocket power. Professor Baxter's figures looked very much better in some respects than those previously published.

One point he would like to draw attention to was Professor Baxter's remarks on the landing of a winged V.2 after its skip through the atmosphere by means of a 1,500 lb. jet engine. It was always necessary to allow for the case when the pilot did not get in first time and went round again, when about twice that power would be necessary.

A. V. CLEAVER (de Havilland Engine Co., Ltd., *Fellow*): This matter was not always quite as easy as Mr. Brennan thought! In fact, perhaps Professor Baxter's lecture was so excellent that it made it seem easier than it was. However, he thought they could cope with the problems involved.

He supported Professor Baxter strongly on his opening remarks that in considering this new type of aircraft, the rocket aircraft, one must not make the mistake of trying to use it in exactly the same way as the more conventional types powered by air-breathing

engines. He would remind them that something like that mistake was made by many people a few years ago in comparing jet aircraft with propeller-driven aircraft. They thought the cross-over point where one changed from one to the other might occur with equal propulsive efficiency. Of course it did not, because a rather different aircraft was designed round the jet engine and it was used in perhaps a slightly different flight plan and this would be even more true of the rocket aircraft. It might even be that eventually, if they did have long-range aircraft flying at very high supersonic speeds, they ought to do as Professor Baxter suggested and, instead of crawling about through the atmosphere at Mach numbers of two or three, they really ought to go outside it and think of it in "Mach numbers" of ten or so.

The rocket engines themselves were of course his particular interest and he would say that there were probably not many cases, in practice, where it paid to use the dispersed layout of the rocket engine, with the pumps being driven by whatever other type of prime mover was fitted to the vehicle. This was superficially attractive but it involved long lengths of piping carrying the propellants with all the difficulties from leaks and possible vulnerability to various things, not least to enemy action. One would also have to face a weight penalty which in a typical case might be anything like a pound per foot run of pipes, which very soon took away any weight advantage there might be from not carrying a turbine using rocket propellants to drive the pumps.

He agreed with Professor Baxter that for aircraft rocket engines it was important to aim for a high performance per gallon per second. Perhaps this was even more important than aiming for a high performance per pound weight per second. For vehicles that operated largely outside the atmosphere such as long-range ballistic rockets, this would be less true and for them there might be a case for using very low molecular weight low density propellants, perhaps even hydrogen, as a fuel. He could not agree more about hydrogen peroxide and thanked Professor Baxter for having made the point for him.

The figures of augmentation of static thrust looked very interesting for the rocket with a duct as thrust augmentor, but the thrust increases merely from this fell off rapidly with flight speed. The really interesting possibility was in considering whether one could not burn the rocket exhaust in the air going through the duct afterwards, so that they had a sort of compound engine, a rocket-cum-ram jet which the Americans very expressively called the "ram rocket." This sort of device was worth considering, at least for some special purposes.

Perhaps Professor Baxter had been a little pessimistic in his estimates of the percentage of the consumption required for pumping. He thought one could improve on the figures even with a conventional layout, by careful detail design of the turbine and pumps, but there were ways of actually using the pump turbines' exhaust which could reduce this figure to something under half a per cent. and this tended to favour the use of rather higher chamber pressures. Had Professor Baxter any second thoughts on that point? Another reason for using a higher pressure was if they wanted to throttle the engine. If they wanted to run the engine at something like ten or twenty per cent. of its maximum thrust, it paid to start off with a high chamber pressure so that they still had a reasonable value, even when the engine was throttled.

The printed paper in discussing the question of cooling, rather gave the impression that a high pressure chamber would be easier to cool because it was smaller and had less surface area. Would Professor Baxter agree that in practice this effect, although it was certainly present, was usually over-shadowed by the fact that in a high pressure engine there was a thinner boundary layer on the gas side and in fact high pressure engines were usually more difficult to cool?

He agreed that while mild steel, purely on the heat transfer and strength basis, was as good a material as any for the chamber, for aircraft engines with a long life and repeated use, he thought they would probably go to heat-resisting stainless steels, if only to provide better scale resistance and resistance to corrosion. Also, in future engines using high combustion temperatures the differences discussed by Professor Baxter would be rather smaller, because if the metal temperatures were getting hotter these differences of conductivity became smaller; all steels approached roughly the same value at very high metal temperatures.

He thought that in a turbo-pump design there was much to be said for having the turbine drive the pumps through a gear box. Professor Baxter advocated a single shaft design; if they had a gear box they could choose the optimum speed to run the pumps but, even more important, some of the sealing problems could be overcome and the hot part of the unit separated from the cold parts with some advantages in overcoming thermal distortion problems and so on.

One point he wished particularly to mention concerned the ignition problem of starting. Personally, in any inhabited rocket aircraft, he would like to have as little to do with self-igniting fuels and oxidants as possible. He thought the German use of them was responsible for much of the impression that rocket propellants were going to be dangerous to handle. He thought they always would be difficult to handle if self-igniting propellants were used, but with non-self-igniting propellants the problem was nothing like so bad as some people thought. Professor Baxter had mentioned the possibility of using in a peroxide motor, for example, a purge of peroxide products, that was decomposed hydrogen peroxide, steam and oxygen, to sweep any possible fuel accumulations out of the chamber. Of course much more than that could be done; these products could be used to light up the fuel because they were hot. If peroxide were decomposed into steam and oxygen there was a source of gases at 500° or 600° centigrade which could be used to light the fuel and light it very safely in a fool-proof manner. He knew Professor Baxter had had quite a lot to do with work on that system and perhaps he might give them his opinions on that. He welcomed very much Professor

Baxter's closing remarks that one of these days the rocket would enable them to fly beyond the atmosphere.

J. E. P. DUNNING (Ministry of Supply): What had impressed him greatly was that Professor Baxter had made it quite plain that they just could not consider an aeroplane and think it could be improved by putting in a rocket. They must start off with the realisation that if a rocket were going to be used it had a major influence on the design of the aeroplane. The rocket combined with another form of engine, an air-swallowing engine, effected a marked change in the performance of the aeroplane. Professor Baxter had high-lighted the advantages of both types of engine and emphasised the high altitude capabilities of an aeroplane so powered.

All air-swallowing engines required ground facilities for their development. A rocket did also but it only amounted to an emplacement for safety's sake, and a fuel supply system. When they considered the types of engine they wanted they must consider the cost of development because the cost of the plant required was an important item and, to some extent, the rocket had an advantage in this respect.

The word "propellant" seemed to be with them but no such word existed in the English language. The word was "propell*ent*" and if the Oxford Dictionary were accepted as their standard that was the word. He had argued for a long time over this; if they needed a word, make one, but when a word existed why make another? The word "propellent" covered all their needs.

Professor Baxter used the word "motor." In the aircraft field they had standardised the term "engine" merely as a matter of convenience. If they called them engines people were more conscious of them being associated with the same problems which affect turbine engines and piston engines and realised that they had to have the same engineering ability and brains behind them to develop them. From the literature point of view also, it simplified the E.D.M.'s to use one term.

H. DAVIES (Saunders-Roe, Ltd., *Fellow*): Supposing an aircraft full of some highly explosive fuel crash-landed, was there danger of an explosion or what would be the consequences?

The Lecturer had touched upon prospects of a civil or commercial application of rocket propulsion. Rocket propulsion might be used for the long-range transport of the future. If they tried to picture this long-range transport, obviously it had to be wingless; it was going to fly in regions where the air was too thin to sustain normal flight.

His ideas were something like this: they were going to have vertical take-off so would not have an under-carriage. There would be a rocket and passengers would climb up some stairway to their seats in this machine. He was not thinking of trying to escape from the earth's gravitational field but trying to use this thing as a long-range transport. They would climb up some sort of external stairway or there might be a lift to take them to their seat in the "aeroplane." They would take off vertically and climb slowly until they reached the thin air, then there would be a burst and it would then be something rather like the V.2. They would climb to a certain height and drop. When they dropped again they would still be above the denser atmosphere during most of the very long glide.

He did not know how the final touch-down would be made. Coming down again they would land with the tail fins first. This rocket had tail fins which were necessary to give the thing arrow stability as it was climbing. The V.2 had these things but the V.2 landed nose first which would not do for passengers. His proposition was that arrow stability could be obtained quite simply if they arranged for a big movement of the c. g. and for very long tail fins. He wanted tail fins to stretch about two thirds of the length of the rocket transport and the fuel to be housed amidships; matters would be so arranged that when they landed, the c. g. would be below the centre of pressure of the air loads on these long tail fins. If that were done they could land with the tail fins first, which was desirable from the point of view of the passengers and possibly, although this was perhaps a little doubtful, they might have a large parachute to break the fall partially on touch-down.

These were merely ideas which he wanted to propound and he wondered what the Lecturer thought about them.

R. P. DICKINSON (Ministry of Supply, Boscombe Down): It was quite obvious that someone had been very busy developing these new power plants and he would like to congratulate those concerned on the notable progress that had been made. He would confine himself to comments from the operators' point of view. In this connection he had heard several references that evening that the flight plan could be adapted to the power units' characteristics. He hoped that this liberty would not be taken too far as, operationally, the flight plan was rather confined, the aim generally being to reach a particular point in space as quickly as possible.

Some of the graphs illustrated thrust per unit frontal area, etc., as a parameter; while the rocket engine obviously showed up well in this way, the Lecturer's own reference to the large frontal area of the fuselage required to stow the fuel rather contradicted the hypothesis of the frontal area of the engine itself.

It was a pity they were now thinking of engines which had, in effect, to carry their air with them; this being reflected in the total volume of "fuel" to be carried. However, he was quite sure that the essential emphasis in research was being given to reducing fuel consumption. One advantage of the rocket was that they would no longer have air intakes to worry about with their attendant complication in tracking down the unexpected deficiencies in thrust.

The Lecturer had emphasised the advantage of the rocket engine for take-off, but his experience was that the landing run, on wet surfaces, was the critical thing. On the other hand the high fuel consumption was resulting in landing weights of a third of the take-off weight and this would help considerably.

R. STANTON JONES (Saunders-Roe, Limited): Anyone who had read Professor Baxter's paper and given some thought to mixed-unit design could not help praising the virtues of the mixed-unit aeroplanes, but he would like to mention one of the virtues and one of the disadvantages of such aircraft.

One of the virtues was that a rocket aircraft inevitably wished to fly at very high altitudes. As Professor Baxter had shown, flight at extreme altitudes entailed large wing areas because of the low air density, and large wing areas eased one of the most difficult problems of the high speed aircraft, which was the landing problem.

Thus an aircraft designed to use a rocket motor and a jet engine, and designed to fly at altitudes up to 80,000 or 100,000 ft., automatically had a low wing loading which eased the landing problem to a very great extent.

On the other hand, if the consumption of the rocket motor was increased by, say, 5 per cent., with a pure rocket aircraft that would just reduce the performance by 5 per cent. But with a mixed-unit aircraft, where the jet engine was used for one part of the flight, and the combined engines in another part of the flight, a 5 per cent. increase in consumption of the rocket would lead to something like a 30 per cent. drop in the jet engine endurance. Therefore it was worth while if even a ½ per cent. reduction of the rocket engine consumption could be obtained.

On the curve which showed the operating point of the rocket motor Professor Baxter showed that the optimum occurred when the motor was running fairly fuel-rich, but the specific impulse obtained from varying the oxygen to fuel ratio did not appear to drop very much from this optimum. It would seem from this that even if the fuel ratio were not quite right the specific impulse would not fall very much. From the curve it could be seen that a 25 per cent. change of liquid oxygen to fuel ratio would give about a 3 per cent. reduction of the optimum specific impulse. This effect might be used to advantage for a mixed-unit aircraft to adjust the fuel available to either unit without seriously reducing the rocket thrust.

DR. E. S. MOULT (Chief Engineer, de Havilland Engine Co., Ltd., *Fellow*): He was particularly grateful to Professor Baxter for his elucidation of the possibilities of this new type of power plant and for his confirmation on a number of points concerning which some doubts had been expressed.

An important fact brought out in the paper and during the subsequent discussion was that the new device was no longer a stunt or a technical trick; it was not even a "motor" but, in very truth, an "engine." Everyone working on rockets for the propulsion of manned aircraft was fully appreciative of what this implied and realised that they must make the new power plant as controllable and as reliable as any other type of aircraft engine. This would involve much work and some time but already the propulsive rocket showed considerable promise.

A point to be taken from the meeting was the very great contribution which a rocket could make as an auxiliary to a gas turbine engine. The added thrust was most valuable during acceleration of the aircraft from one speed to another and in assisting manoeuvrability at altitude. Whereas the thrust from a turbo-jet at 60,000 ft. was, perhaps, only ⅛ per cent. of its thrust at sea level, that from a rocket would improve slightly. Thus, if a rocket of equal sea level thrust were added to a turbo-jet installation, the combined thrust at 60,000 ft. would be increased by no less than ten times. It was understandable that such an increase in power would transform the performance of an aircraft just at a time when the thrust from an air-breathing engine was on the decline.

He agreed that weight and frontal area per unit of thrust did not have the same significance as for an air-breathing engine. In general, the installation of a light and compact engine was not a major problem and, in any case, the picture was over-shadowed by considerations of fuel consumption. When one remembered that a rocket engine might consume its own weight of fuel in, perhaps, twelve seconds, it was obvious that in operation it had to be used appropriately.

Professor Baxter had rightly emphasised the influence of the new power plant on aircraft design. It was equally important that the rocket should be operated correctly and used particularly at those times when a large increase of thrust was needed for short periods of operation.

N. E. ROWE (*Chairman*): Before proposing a vote of thanks to the Lecturer he would like to speak for two minutes as Chairman of the Branches Committee and say how much they were encouraged in their work at the Headquarters by gatherings such as this, to say how much they felt — and this was shared by the whole Council of the Society—that the work of the Branches had a tremendous influence on the sphere of aeronautics in this country, on the dissemination of information that was correct and properly understood and, generally, in leading forward in aeronautical matters. The Branches, by their very constitution, and they were spread over the country—from the Isle of Wight to Glasgow and east to west from London to Merthyr Tydfil—ensured that the Society reached out to people in a way which would be quite impossible if it remained as a London Society. And of course the constitution of Branches, autonomous bodies having membership of people who could not otherwise be connected with the Society, enabled the aeronautical knowledge and lectures such as this to be spread to a far wider circle than could otherwise be achieved. So that an occasion such as the present was a tremendous encouragement to the Branches Committee and he would like to thank the Officers of the Isle of Wight Branch who organised things and particularly Mr. Rosenthal, the energetic and effective Secretary. He would also like to thank the Company who he knew did a tremendous amount to help the Branch in many ways, especially on an occasion of this sort when they made everything so easy for visitors and extended the most kindly hospitality.

He was trying while he was President-Elect, and while he held the office of President, to visit all the Branches in the country and if they would be so kind as to take this as a visit he would be grateful. If he could visit them again he would, but it was one off his conscience!

They had heard that evening what he thought was a classic lecture in a new field. Everyone agreed that they were entering a brave new world. They were no longer going to crawl about inside this earthy atmosphere at a Mach number of three. They were going out into the outer spaces to fly at a Mach number of ten or twenty. How they got to a Mach number at all when there was no atmosphere he did not know, but doubtless this would "come out in the wash"! They had heard an account of the new engines which would help to achieve these advances which everyone agreed was lucid, comprehensive, and he was sure this would be a standard paper to be consulted. It had been given by a great authority and they were indeed fortunate to have Professor Baxter come and give this paper at the Branch. On their behalf he offered him their very best thanks.

J. A. WILLIAMS (Laporte Chemicals, Limited) *contributed*: As he belonged to a firm manufacturing hydrogen peroxide he was very glad that Professor Baxter thought it was pre-eminent. There should be no difficulty in handling it into aircraft on the ground by the design of suitable installations, tankers, hoses, couplings and other ironmongery that was fully compatible. Refuelling in the air was only a forward-looking extension of this practice and cut out the heavy consumption which would occur each time a solely rocket-powered aircraft took off after coming in to refuel. His idea was that it should be done over the sea and the altitude at which this would be practicable would have to be found out, the aircraft coming down from, and climbing away up to its normal cruising height Therefore it seemed the use of auxiliary engines could be done away with, with accompanying saving in weight, space and fuel, the initial take-off being by jettisonable-assisted take-off rockets—as the de Havilland Super Sprite.

As a student of rockets for aircraft and other applications he would use Professor Baxter's paper as a valuable source of reference. In his study of bi-propellant rockets he wondered if it were correct to favour the use of the turbine, and two-pump system normally accepted because of its simplicity. Was it because it was demonstrated by the Germans to have some advantages and ought they not now to consider other systems of prime mover and pumps? A turbine for maximum efficiency operated at high speed and this might not suit the specific speed of the pump designed for handling the fuel and oxidant at the conditions required at the combustion chamber. Various paliatives had been put forward to try and reconcile these conflicting conditions — as the helix or "booster stage" in contemporary design of pumps. Did this not also mask the formation of a forced vortex in the suction pipe of a centrifugal pump noted by recent workers as lowering its efficiency when working throttled, plus the effect of cavitation and erosion at all times? He would be most grateful to have Professor Baxter's views on these and his suggestion of using a turbine driving a variable delivery pump through a gearbox. Proper design would take care of the weight and the turbine could be smaller and lighter and run at a higher speed.

There was also the question of the control of the circuit of centrifugal pumps which mainly fed the combustion chamber but also the gas generator, which supplied the turbine which drove the pumps. Did not this tend to be an unstable closed circuit involving changes in state and pumps in parallel needing complicated controls? Would it not be better to use a reciprocating engine which was less sensitive to changes? At the same time its lower speed would suit the pumps of either type better.

The efficiency of an up-to-date design would compare with the present simple type of turbine of one or two rows of blading and it could be designed for minimum weight.

PROFESSOR BAXTER'S REPLY

He regretted that time had cut short the discussion, but appreciated the many points put forward within the limited period available. He was glad to note that many of them supported his statements in the lecture and that others had been largely answered by the speakers themselves. In reply to the remainder, he had the following to say:—

MR. BRENNAN: He was quite correct in assuming that the record altitude of the Bell X-1 aircraft shown on Fig. 6 was achieved after launching from a B.29 Superfortress parent aircraft at about 35,000 ft. Such an arrangement was not essential to reach high altitudes, but it obviously saved propellant in the regions where air-breathing engines could operate satisfactorily. This would reduce the weight of the rocket aircraft for a given performance or alternatively give it a better one for the same weight. The composite aircraft might well be one of the flight techniques developed for this form of propulsion. It could possibly be applied to the landing case also and then the question of extra jet engine thrust to allow for the baulked landing case would not arise.

MR. CLEAVER: He was probably right in preferring the turbine driven pump layout to the mechanically driven arrangement. The latter could have advantages in special cases, but in general it was more satisfactory to fit a self-contained engine which could be tested as a completely independent unit. In the other case, any

loss in main engine speed would affect the rocket engine performance and at great enough heights this was bound to occur.

Paradoxically, Mr. Cleaver suggested using a gear-box with the turbine drive. This did enable fuel pump, oxidant pump and turbine to operate individually at their best rotational speeds, but he was doubtful whether there would be any total weight saving as a result and he did not think the mechanical problems were eased sufficiently to justify it.

With regard to the propellant consumption necessary for driving the pumps, it was agreed that the figures in the paper might be on the conservative side. This policy had been adopted for all performance figures in order to avoid any accusation of over-optimism. He was quite prepared to accept that modern developments had made considerable reduction possible and he believed that there was still ample scope for improvement. Even at Mr. Cleaver's figure of one half per cent., the overall efficiency of turbine and pump was less than ten per cent.

Mr. Cleaver's arguments in favour of higher pressure combustion appeared to be balanced by his objections and the result would seem to be that, as the paper suggested, the best compromise lay somewhere between 300 lb./in.^{2} and 600 lb./in.^{2}. He did not think that the degree of thrust variation which should be expected from a rocket engine justified designing the combustion chamber for very high pressures and the point made about the increased cooling difficulties was very real. It was unlikely that the boundary layer thickness would be greatly altered by change in pressure, but gas radiation per unit area would increase and dissociation would be less. The latter would result in a higher combustion temperature; for example, the oxygen/petrol mixture shown in Fig. 19 had a maximum temperature of 3,400°K at a pressure of 300 lb./in.^{2}, but this would have risen to 3,500°K at 600 lb./in.^{2}. Furthermore, the larger expansion ratio would involve a divergent nozzle surface area about 80 per cent. greater being exposed to hot gases and the cooling of this would more than counter-balance the reduced area of the combustion space. He did not regard the use of heat-resisting stainless steels as essential to resist scale and corrosion. Mild steel could be protected by surface plating or in other ways and such surface treatment could provide some thermal protection. With present techniques, however, such treatments did not last for a prolonged running life and on this count there was something in favour of using a stainless steel. It was also true that differences in conductivity became less as the metal temperature increased, but at 700°C mild steel still had a thermal conductivity nearly 50 per cent. better than most heat-resisting alloys.

He agreed entirely with Mr. Cleaver's remarks on normal self-igniting propellants and was glad that he had mentioned the "thermal" ignition method of using hydrogen peroxide. It eliminated all the undesirable features of the normal rocket engine starting process mentioned in the paper and gave a very neat arrangement.

MR. DUNNING: He pointed out that the development test facilities for rocket engines were much less than for other types of engine. This was correct, but it should not be imagined that there were no problems attached to them. Not only was it essential to protect personnel from the risks of engine failures during development, but it was also necessary to deal with such problems as the disposal of propellants which were spilled, without harmful results to man or beast. The problems of recording the engine performance demanded special instrumentation techniques and there was a good deal of other specialised equipment involved.

With regard to the word "propellant," this was the American spelling and as they were in the liquid field before, it had been largely accepted over here. He had used "engine" and "motor" in the same sense and was quite happy to standardise the former although, using Mr. Dunning's own reference, the Oxford Dictionary, the latter seemed more appropriate.

MR. H. DAVIES: The consequences of a crash with propellant tanks full could vary widely. In appropriate conditions with fuel and oxidant mixing rapidly and possibly some ignition source present, a fairly heavy explosion could occur. On the other hand, the liquids could spill quite harmlessly. It was quite possible to mix kerosine and hydrogen peroxide, for example, quite intimately without any reaction occurring. The most likely result of a crash would be similar to that of a normal aircraft, that is, a risk of fire.

Mr. Davies' ideas on rocket aircraft design and operating techniques were interesting, particularly with respect to landing tail first by changing the c. g. position. This could be easily arranged by suitable lay-out of the propellant tanks in the fuselage, but he believed that designers usually objected to a large shift in c. g. This might not be important during an almost vertical climb, but once the long glide commenced, the arrow stability would produce a drastic re-orientation of the fuselage which passengers might not find acceptable and which he imagined Mr. Davies only wished to introduce during the final stages of landing. Nevertheless, some form of vertical landing might well be considered.

MR. DICKINSON: His remarks were primarily in connection with the aircraft operating side. He had pointed out that landing was a critical condition for most aircraft, but it should not be with the low landing weight of the rocket powered machine. Actually the paper had generally assumed landing conditions similar to those of normal aircraft and put up the take-off loading to a higher value. It was, of course, possible to compromise between the two conditions if necessary, and there might be other ways of dealing with it as had been indicated in replies to earlier speakers.

With regard to flight plan, he felt that Mr. Dickinson was taking a conservative view of flight and he could only re-emphasise that, provided new techniques did what was wanted better than the conventional way, they should be adopted.

MR. STANTON JONES: The point raised about the relative endurance of pure rocket aircraft and mixed

unit aircraft when the rocket propellant consumption varied, depended upon whether the specific consumption increased at a constant mixture ratio due to combustion or other inefficiencies, or whether it increased because the mixture ratio varied. If the former, Mr. Stanton Jones would be generally correct if it were assumed that the turbo-jet engine endurance was reduced in order to keep the rocket endurance the same. This would not usually be the case because the oxidant tank would be designed for a fixed quantity of propellant and could not be adjusted in flight. The rocket endurance would, therefore, be reduced exactly as in the pure rocket aircraft and the turbo-jet endurance hardly affected.

On the other hand, if mixture ratio varied, the result would be more complicated. Assuming the propellant flow was adjusted to give the normal thrust, a change of liquid oxygen/fuel mixture from 2·5:1 to 2·0:1 would mean a reduction of 2·5 per cent. in oxygen flow rate and an increase of 25 per cent. in fuel flow rate. Thus the rocket engine endurance would be increased slightly, but the turbine engine would have a greatly reduced quantity of fuel available. If, instead of these propellants, hydrogen peroxide/kerosine had been used, the best mixture ratio would have been 8·0:1 and a similar proportional change would have been to 6·5:1. In this case, the peroxide consumption rate to retain normal thrust would have increased by 3 per cent. and the fuel by 22 per cent., but as the fuel was a small proportion of the total propellant flow, the reduction in fuel available for the turbine engine would only be 10 per cent. instead of 30 per cent. in the previous case.

Such large variations in mixture ratio should never happen accidentally, but it might be noted as another virtue of the hydrogen peroxide systems, that they were usually designed for a mixture ratio which gave gas temperatures very close to the maximum so that any accidental changes in mixture could only produce a lower temperature. Liquid oxygen operating mixtures were at temperatures below the maximum and a fuel variation which brought the mixture nearer to stoichiometric might cause over-heating of the combustion chamber.

MR. WILLIAMS: Refuelling of rocket aircraft in flight might be one of the new techniques necessary to exploit them fully, but there were obvious difficulties. It would be necessary for the rocket aircraft to have sufficient propellant available to contact the tanker aircraft and the refuelling process would have to be very rapid if the actual consumption during refuelling was not to be too large. It might, of course, be possible to hook on or be towed with engine stopped during the operation.

It was true that the two pumps and turbine on a single shaft called for a design compromise on rotational speed, but it was usually the pumps which demanded the high speed. One solution to this was, as suggested by Mr. Cleaver, to employ a gearbox. Cavitation at the pump inlet was primarily a result of the propellant pressure being lower than its vapour pressure and could be avoided by ensuring that the depression at the eye of the pump was not too great or by boosting the pressure at entry either with some form of booster pump or by pressurising the tanks.

Although the paper had not gone into detail on the stability of the turbo-pump drive, there was no major difficulty in ensuring steady operation, and the use of a reciprocating drive could not be justified on that score.

*The Second Barnwell Memorial Lecture**

The Outlook on Airframe Fatigue

by

WALTER TYE, O.B.E., B.Sc., F.R.Ae.S.
(Air Registration Board)

Introduction

My pleasure in accepting your invitation to lecture, which I treat as a great honour, has been somewhat overshadowed by doubt that I shall do justice to the occasion. This is but the second lecture to commemorate Captain Frank Barnwell. I am fully alive to the fact that the members of this Branch of the Society, many of whom were Captain Barnwell's personal friends, are very desirous of establishing, in these early lectures, a standard which is a worthy memorial.

Captain Barnwell was one of a small number—I suppose they can be counted on the fingers of two hands—who, by their courage and ability, made the barely flyable contraptions of 50 years ago into the aeroplanes we know today. The changes in aeronautical engineering have been so great that it is not easy to realise in 1955 the problems Barnwell and his colleagues faced in 1905, the year of the first Barnwell designs.

When one thinks back of the absence of data, the lack of test equipment, the knowledge that every step was taken in the dark, the magnitude of these men's work becomes clear. I have often wondered what ability these pioneers possessed which distinguished them from their fellows. In addition to the attributes of courage and single-mindedness of purpose, they must have been blessed in full measure with that nebulous quality vaguely called "engineering instincts." I am inclined to believe that, as aeronautical knowledge has grown, our instincts may have deteriorated, or at least they have not been permitted to develop. This is not a good thing, as much in aeronautical engineering is still dependent on judgment rather than on purely scientific method. An example of this is to be seen in the subject of this paper.

I have chosen to discuss airframe fatigue, an old complaint which has appeared recently in a virulent form. In choosing this subject I did so in the belief that, despite the abundance of articles, lectures and conferences, a few more words can still usefully be spoken.

Pre-1945

Fatigue of metals has been a matter with which designers have had to contend for a very long time. Fatigue was recognised as a distinct form of failure, *i.e.* differing from ordinary static load failure, about 100 years ago, and was first discussed in a paper in 1854. Since then, a vast amount of empirical data has been collected. Naturally the bulk of this information refers to irons and steels and is more relevant to conditions in which the cycles of stress are relatively low and are repeated enormous numbers of times—such conditions as exist, for instance, in parts of a reciprocating engine.

Broadly speaking, these data have little relevance to the structure of an aeroplane, partly because of the use of light alloys, partly because the loads applied include everything from a few high loads to many low loads. Moreover, the information usually refers to specially designed test specimens, smooth bars under axial or bending loading. No airframe structure employs materials made up to look anything like these test specimens.

Absence of data did not seriously embarrass the aeroplane designer before the Second World War. When failures occurred they were rarely catastrophic and often associated with some obvious source of vibration. They were often attributable to poor detailed design, and hence were not difficult to cure. This absence of trouble may have lulled some of us into a false sense of security. Considerable attention to fatigue was devoted by German and Swedish research workers in this pre-war period. It is interesting to note that many of the fatigue test machines used at present are of German design and construction.

Meanwhile, in the years preceding 1945, a number of overall changes were occurring. These have been examined fairly recently by R. V. Rhode.[1] He concluded that the chief factor which had tended to reduce fatigue life was the improvement in static structural efficiency, which had allowed structures to be designed to function at higher stresses. His calculations, which were perhaps illustrative rather than numerically precise, showed a staggering reduction in fatigue life of wing structures between 1934 and 1946.

Owing to the concentration of effort in improving the structural efficiency in respect of static loading, a demand arose for light alloys with higher ultimate and proof stresses. The new alloys, such as D.T.D. 363, 364, and 683, had no better fatigue properties than the earlier alloys on a comparative stress basis. Thus, for structures of equal static strength a reduction in fatigue life occurred. For instance, Rhode shows about a five-fold reduction in fatigue life in transferring from 24 S.T. to 75 S.T. material.

*Given to the Bristol Branch of the Society on 8th March 1955.

Another and more obvious change was the demand in civil aircraft for long lives, 30,000 hours being considered reasonable, whereas earlier, 10,000 hours would have been considered remarkably nigh. Probably it was this trend, rather than the more insidious and far-reaching effects previously described, that caused a few people to think about the fatigue problem.

1945-1955

The early post-War years saw the construction of several types of civil aeroplanes. The designers of these aircraft were by no means inactive in regard to fatigue. Tests were done on typical joints, and this kind of work showed the considerable improvements in fatigue life rendered possible by attention to detailed design. The value of this work was limited by lack of knowledge of the loads to apply, and the small scale of laboratory equipment. Nevertheless, on a comparative basis, it showed what was good and what was bad.

In addition to this, *ad hoc* testing preparations were made, in particular at the Royal Aircraft Establishment, to install large testing machines, and designs of suitable gust counting recorders were put in hand. One of the objects was to enable lives of main components, such as spars, to be established with some certainty. Research work into fatigue did not however proceed very fast. It was, in fact, regrettably slow in the light of subsequent events, but it must be remembered that there was, at the time, no widespread agreement on the importance and urgency of the problem.

In looking back over the records one sees a few important and far-sighted contributions. Pugsley[2] in 1947 drew attention to the adverse design trends, and concluded that the life of conventional wing and tail structures would not be remote from that contemplated commercially.

The most notable contribution of these times was the paper by Walker[3]—"Fatigue of Aircraft Structures." Having re-read this paper recently, I doubted the wisdom of lecturing on the same subject tonight, for P. B. Walker dealt with the matters so fully six years ago. However, whereas in certain aspects Walker was prophesying the future, it is now possible to confirm his forecasts by experience.

Walker's paper provided what the layman calls "A Blue Print"—a kind of general plan into which all aspects of fatigue were fitted. As a lengthy quotation is not possible here, the following only is given:

> "In the light of these preliminary considerations, fatigue is seen as a serious problem in aircraft design, and one requiring study from the design standpoint over and above what it may also require as a fundamental scientific problem."

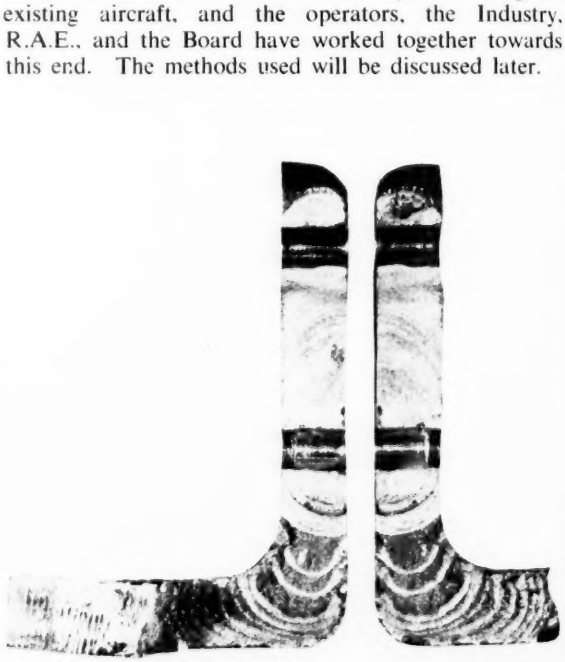
In so far as there are milestones along the road which aeronautical engineering thought travels, this is clearly one of them.

However, expert opinion as to the seriousness of the problem was by no means unanimous until late 1951, when two events occurred which swept away the doubts. During an inspection of a fatigue-suspect area, one of the two lower spar booms of a Viking spar was found to be completely severed by fatigue, Fig. 1(*a*). At about the same time a Dove in Western Australia suffered a fatal accident due to fatigue failure of the single lower boom of the centre section spar, Fig. 1(*b*). A sister aircraft which had flown a similar large number of hours was found to be seriously cracked in the same region.

Following these two events an all-out drive was started to establish safe lives of the spars of wings of existing aircraft, and the operators, the Industry, R.A.E., and the Board have worked together towards this end. The methods used will be discussed later.

(Reproduced by courtesy of Vickers-Armstrongs Ltd.)

FIGURE 1(*a*). Typical spar fatigue failure (Viking).



(Reproduced by courtesy of The de Havilland Aircraft Co. Ltd.)

FIGURE 1(*b*). Typical spar fatigue failure.

At first it seemed that tests on the apparently critical portion of spar would suffice. However, an exploratory fatigue test on a complete wing by the R.A.E. showed the value of such tests, as the principal failure occurred in the spar at a point other than those sections which had previously been considered to be critical. This first test has been followed by other complete wing tests, both at R.A.E. and at firms, and in every case valuable lessons have been learned. In one case where the skin contributed substantially towards the strength, the tests induced cracks of a potentially serious kind in the skin cover.

With the introduction of pressure cabins after the war, the need to make repeated loading tests on pressure cabin structure became evident. Most of these tests were made on full-scale structures representative of the cabin, but not on a full length cabin. The object of these tests was primarily to assist in making a reliable structure and it was considered sufficient to include representative samples of typical windows, doors, and so on in the test structure. No specific attempt was made to relate the results of these tests to a safe fatigue life of the cabin.

This attitude towards tests on the pressure cabin persisted until 1954 when, following the two Comet accidents, the R.A.E. made a tank to accommodate a full length cabin with its wings attached. This piece of apparatus has been well described in the Press, so no detail will be given other than to recall that it permits the simultaneous testing of a wing and cabin under repetitive external loads from flight and landing and under internal pressure loads.

With the Comet 1 which was tested by R.A.E., a catastrophic type of failure occurred after the equivalent of 9,000 hours flying, the origin being a tiny fatigue area which developed into a crack several feet in length. An alarming feature of this test result was the demonstration that skin cracking was not, in this case, an innocuous matter capable of inspection before reaching dangerous proportions.

Thus, coming to the present day, we are finding ourselves faced with the prospect of extremely costly fatigue testing, embracing tests on components, such as spar sections and window cut-outs, and culminating in a full-scale check on a complete airframe.

Safe Life of Spars

Problems will be discussed next connected with the life of spars, and in particular fixing a safe value of the life. The basic ingredients of the estimate are the load spectrum to which the spar is subjected, and the *S-n* curve of the spar.

The main fatiguing loads in the lower flange of a spar are usually caused by gusts, so if the pattern of gusts in the atmosphere is known, and the operational characteristics of the aircraft (*i.e.* speeds, weights, times on climb, and so on), it is possible to assess the load spectrum applied to the spar.

Information on gust magnitude and frequency has principally come from the R.A.E. Counting Accelerometer. This instrument, and the method of analysis of the results, has been well described by Taylor[4, 5] in recent lectures. The data, which three years ago was almost non-existent, is growing daily and there are now of the order of 10,000 hours of recording.

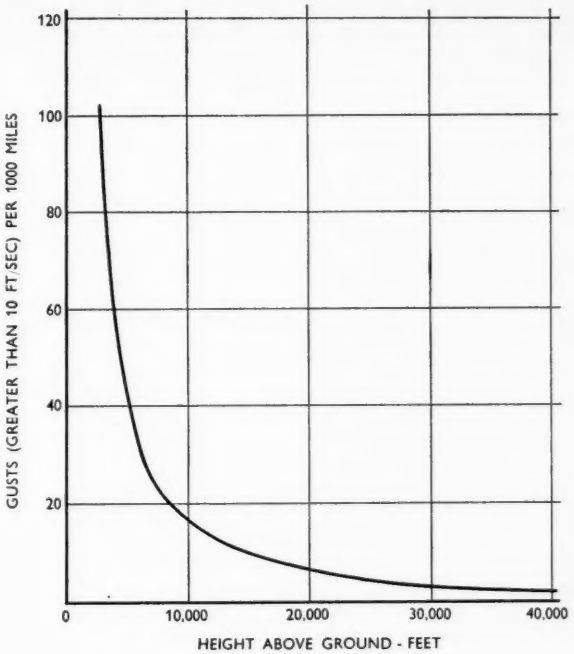


FIGURE 2. Frequency of gusts at different heights.

Analysis of this gust information shows that:—

(*a*) the relative frequency of gusts of various severities is reasonably constant; for instance, 100 gusts over 10 ft./sec. occur for every one gust over 25 ft./sec;

(*b*) the absolute frequency of gusts of a given severity is primarily dependent on the altitude above the local terrain.

The first conclusion is supported by a vast amount of *V-g* recorder data.

As regards the second, Fig. 2 shows gusts (of 10ft./sec. or more) per 1,000 miles against altitude. The data for this figure are taken from Ref. 5. The great difference in frequency between low and high altitudes is most striking. Results obtained from a particular aeroplane type flying on a particular route may differ from generalised curves—such as Fig. 2—the differences possibly arising from geographical zone, whether over water or land, season of the year, and so on. However, from the records so far available, these differences are small compared with the altitude effect.

Although the proportion of time spent in climb and descent at low altitudes is usually a small proportion of the total flight time, the greatly increased frequency of gusts near the ground results in this part of the flight being the most damaging. For instance, in a flight of 2½ hours (cruising at 15,000 feet) of which 12 minutes only (8 per cent. of the total) is spent below 4,000 feet, two-thirds of the total fatigue damage occurs in this short period below 4,000 feet.

Because gusts are so infrequent at altitudes of 10,000 feet or above, the direct benefits to be gained by cruising at high altitudes—such as 40,000 feet—are very small. The high altitude aeroplane gains chiefly from the fact that it climbs quickly through the lower altitudes and, in association with longer flight times, this minimises the proportion of time spent at low altitude.

The great importance of the time spent between the ground and, say, 4,000 feet throws various matters into prominence:

(*a*) It is important to obtain far more data on gust frequency at these low altitudes; unfortunately, but inevitably, only a small fraction of the total records provide relevant data.

(*b*) One suspects that such matters as the nature of the ground over-flown will have more bearing at low altitude than at high, so such differences require careful exploration.

(*c*) The average time spent at low altitudes as a proportion of total flight time, must be assessed very accurately when establishing safe lives of structures.

Information on the operational characteristics of the aeroplane (*i.e.* speeds, times at various heights, and so on) can be derived either from analysis of pilots' reports, or from records from the Taylor accelerometer. The importance of knowing these conditions cannot be over-emphasised. For instance, an under-estimate of speed of 5 per cent. would cause an error in the life estimate of the order of 20 per cent. For a typical case an error of 5 minutes in the time assumed to be spent on climb to, and descent from, 4,000 feet could reduce the life by 20 per cent.

Thus, if generalised data are used, a conservative factor on the gust spectrum and operating conditions is essential, and at the present time the only really satisfactory answer is to obtain actual readings of the particular aeroplane on the particular route.

The second main ingredient of the life estimate is the fatigue life of the component as established by laboratory tests. Generally speaking, it is not practicable to make tests under the spectrum of loads experienced in operation. One is usually limited to testing say, half a dozen nominally identical components under a combination of a steady load corresponding to level flight conditions with a fluctuating load corresponding to regular up and down gusts of the order of 10 ft./sec. magnitude.

These tests give an average of the cycles to fail and it is then necessary to convert the results to the equivalent number of hours flying. This conversion process entails the following main assumptions:—

(*a*) that the cumulative damage rule holds good;

(*b*) that the *S-n* curve follows a certain standard shape (unless sufficient tests have been made to provide data at various stress levels).

This method of estimating lives forms part of a paper by Keri Williams[6] and has been further examined by Chilver[7].

For (*a*), the use of the cumulative damage rule, consider Fig. 3. On this is shown a typical load spectrum, corresponding to 10,000 hours flying. The loads are divided into "packets," for example, 10,000 applications of loads occur in the bracket 10 per cent. to 14 per cent. of ultimate stress. A typical *S-n* curve for a spar component is also shown. At a stress level of 12 per cent. the cycles to fail is $1{\cdot}1 \times 10^5$.

Now, according to the cumulative damage rule, if stresses s_1, s_2, s_3, and so on are applied n_1, n_2, n_3, times respectively, and if a stress such as s_1 applied alone would cause failure at N_1 cycles, then failure under the mixture of loads occurs when

$$\left(\frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3} \ldots\ldots\right) = 1$$

Thus, in terms of stresses in the bracket 10 per cent. to

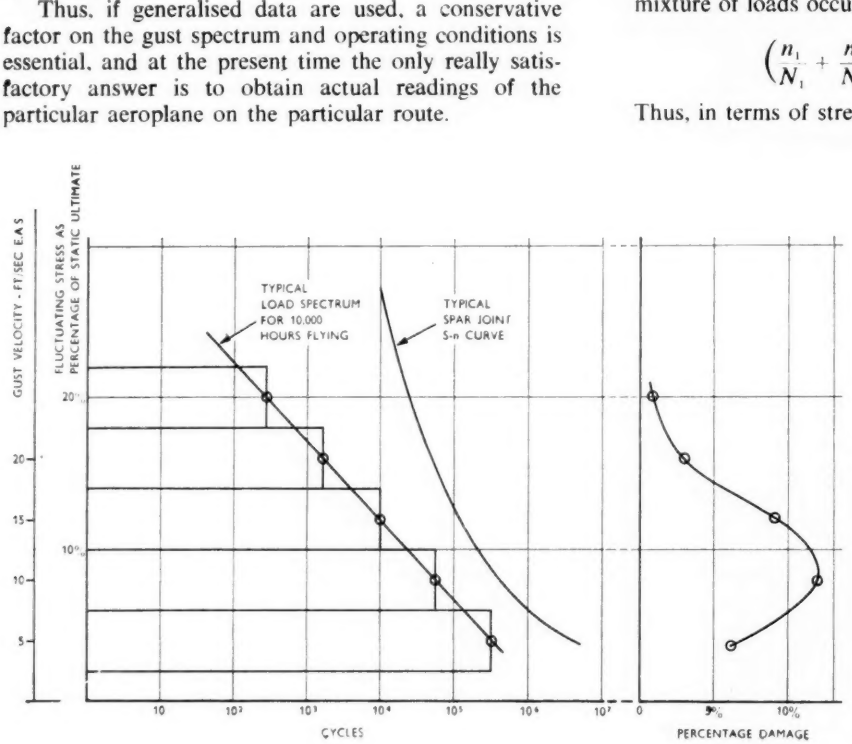


FIGURE 3. Example of the use of the cumulative damage rule for estimating spar life.

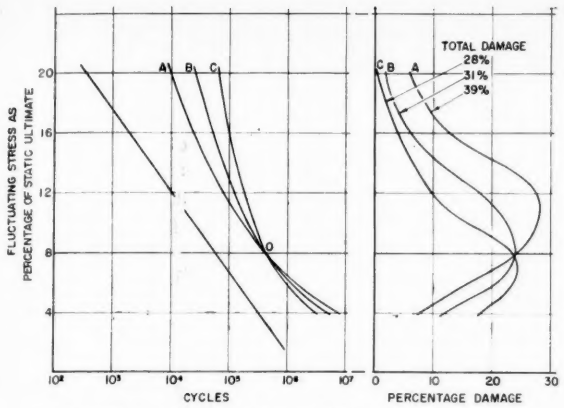


FIGURE 4. Effect of different shapes of *S-n* curve.

14 per cent. of ultimate, the percentage contribution to the damage is

$$100 \times \frac{10^4}{1{\cdot}1 \times 10^5} = 9 \text{ per cent.}$$

The curve on the right in Fig. 3 shows the percentage damage done at various stress levels. It will be seen that if the cumulative damage rule is true, most of the damage is done over a relatively narrow band of stresses, between 4 per cent. and 14 per cent. of ultimate, the most damaging level occurring at about 8 per cent. of ultimate. In terms of gusts to produce this loading, typically a 10 ft./sec. gust is the most damaging.

It is the usual practice to make the laboratory tests at the level of stress likely to be most damaging. Having done this, the use of the cumulative damage rule is less prone to serious error as it becomes a relatively small correcting factor to allow for the effect of loads above and below the most damaging level. However, this argument rather begs the question and I look forward to confirmation or otherwise of the cumulative damage rule.

Grave doubts have been expressed about the use of cumulative damage rule, and it has been demonstrated to be incorrect when loads are applied in certain sequences. However, the gust load spectrum, although random is, if taken over long periods, a reasonably repetitive pattern. That is to say, if one takes a period of 10,000 hours flying and divides it into 10 equal periods of 1,000 hours, the loads applied in any 1,000 hour period will be closely similar to those occurring in any other similar time period. This point was first brought out by Dr. D. Williams[8] and is dependent on the fact that large numbers of loads are applied in the time periods concerned. This fact seems to increase the prospect of the cumulative damage rule being a fair guide in this particular application.

Turning to (*b*), over the important part of the *S-n* curve, the variation in shape is often fairly small, so having determined the relationship between stress and cycles at a particular stress level, it is not unreasonable to draw a standard shape of curve through the point. Errors can arise as shown in Fig. 4, the particular damage caused by the loading spectrum shown, for the three *S-n* curves being 39 per cent., 31 per cent. and 28 per cent. Each of these *S-n* curves passes through the same point *O*, and hence if fatigue test results were available for this point only, the errors in life estimates would be about 20 per cent. too high for *A*, and 10 per cent. too low for *C*, calling *B* the standard.

The final step in determining a safe life is the need to take account of the variation of life of nominally identical structures. Tests on joints indicate that the life of the weakest component of a large batch may be as little as one-third the average life, and the one with the longest life three times the average. The figures vary from case to case, but for immediate purposes the 9:1 or 10:1 ratio can be taken as typical. At first sight this is a surprisingly large scatter. However, it is instructive to think for the moment of scatter as the variability of the stress to give a particular life, rather than the more usual concept of variability of life at a particular stress.

In Fig. 5, line *XX* is a small piece of a typical *S-n* curve for a joint, drawn for convenience in illustration as a straight line, but having the correct general magnitude and slope between 10^5 and 10^6 cycles. A number of parallel lines are drawn above and below, spaced at 0·01 gap representing increments of stress of 10 per cent. about the stress of 0·1 at the mid-point *O* of line *XX*. (A stress of 0·1 means a fluctuating stress of ±0·1 of static ultimate).

It becomes clear from this diagram that a component which on the stress basis is 10 per cent. above average will have a life about 1½ times average, or one which is 10 per cent. below average on a stress basis will have a life about two-thirds of average. Equally, if we look at the outermost line, components which are 30 per

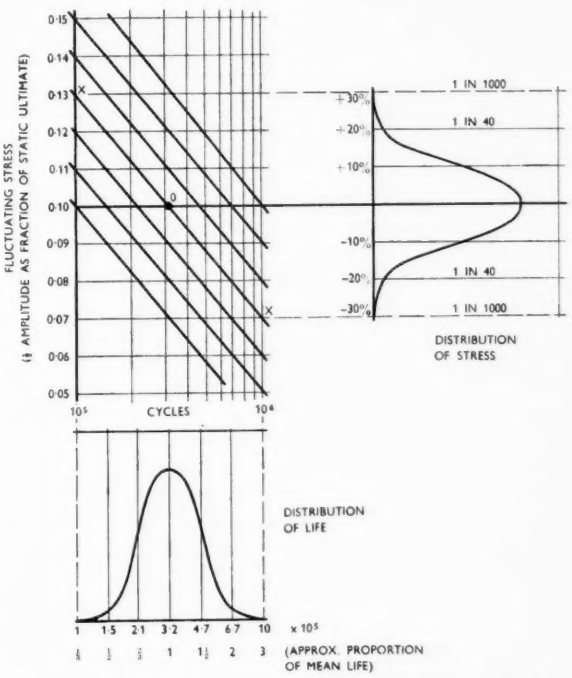


FIGURE 5. Illustration of the scatter of fatigue characteristics.

cent. above and below average on the stress basis have lives of about three times and one-third respectively of average.

Hence, a scatter of life of the order of 9 to 1, or 10 to 1, is equivalent if viewed as a scatter on the stress basis of ±30 per cent. This latter does not seem quite so surprising.

There is some evidence to suggest that variation of life—at a particular stress level—is in accordance with a log normal distribution. This is illustrated by the curve plotted in the lower portion of Fig. 5. This curve represents fairly typical distribution in which one component in 1,000 will be as low as one-third, or as high as three times, the mean.

The consequences of scatter are serious. It is the usual practice nowadays to test about six components, and from these results to obtain a logarithmic mean, then dividing by a factor of about 3 to obtain a safe life. (This factor is exclusive of any factor to allow for ignorance of the external loading). The safe life so obtained is then presumed to be consistent with odds of an order of 1,000 to 1 against failure occurring if an aeroplane flies up to its safe life.

Two main assumptions underlie this calculation:—

(*a*) that the mean life obtained from the six or so results, is a good estimate;

(*b*) that the scatter pattern is the same for all components.

Neither of these assumptions stands up too well to examination.

Firstly, referring to (*a*), it is clear that with the small numbers of test pieces, drawn from a population with a wide scatter, the chances that the experimental mean will closely approximate to the true mean are not high. As for (*b*), the prospect of obtaining from a few results an accurate idea of the scatter is even poorer. It is for this latter reason that it is at present preferred to use a standard scatter, than to use an inadequate sample to obtain the particular value.

These matters have been studied by Kennedy[9]. He uses statistical methods to determine the additional allowance which should be made when information is limited to few specimens. His calculations are used to obtain the example illustrated in Fig. 6. Suppose that we have results of n tests and that these indicate an average life represented by 1·0, and a scatter such that a life of 0·32 of average occurs once in 1,000 occasions. Now, the true mean could be lower or higher, and the scatter greater or less, than the experimental values. Hence there is no certainty that the "safe life" will be 0·32. By using statistical methods it can be said with 90 per cent. confidence (*i.e.* with 9 chances out of 10 of being right) that the safe life indicated by the experimental results will be no lower than the curve shown in Fig. 6. Thus, if there are but six results from which the safe life is deduced to be 0·32, there is in fact a one in 10 chance that it will only be 0·14.

This is very discouraging. It means, among other things, that one can feel more confidence than is justified when a standardised degree of scatter is assumed, even when the experimental results support using the standard value. It also means that if the component tests indicated low scatter, it would be unwise to accept the indication unless many results were available.

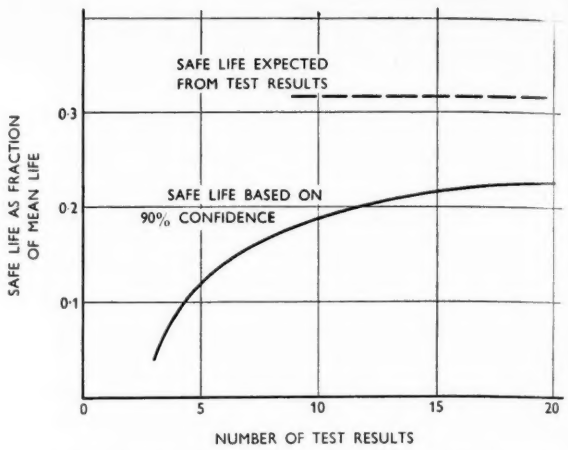


FIGURE 6. Effect of number of test specimens on estimated safe life.

Wing Tests

As already mentioned, a complete wing test is of value, but its limitations must be appreciated. Such tests have resulted in failures in spar and skin at unexpectedly low lives and in positions not suspected of being critical. Another benefit is that the tests indicate the kind of failure, *e.g.* whether cracks are of a safe "seeable-before-catastrophe" kind or not.

The limitation of wing testing is bound up with the scatter problem. Usually it is practicable to test one wing only. One cannot assume that the test wing is an average one. If the scatter is assumed to be of the usual order, then with 97½ per cent. confidence the life of the test wing can be put at not more than twice the average. Hence to establish a safe life result from a single test result means dividing by a factor of 6 (excluding any factors on the gust spectrum).

A test might be done at the rate of one minute testing equalling one hour of flight. So to establish 30,000 hours of safe life means 3,000 hours testing, or four months continuous running. In practice, owing to the difficulties of providing continuous 24 hour-a-day watch and due to time taken to repair, the time is very much greater—a year or 18 months would be more likely.

If, during testing, local failures occur of a repairable kind, the test can continue and the life of the particular part established more precisely by testing several detailed specimens. For these local areas, additional testing would permit reduction of the factor. But the main test would have to proceed to a number of cycles greatly in excess of the desired operational life if it were to be relied on to establish that all weak points had been detected. This may raise difficulties, as minor cracks, if sufficiently numerous, may make the test unrepresentative.

Because of these difficulties, it is unlikely that a wing test can be relied on to provide indisputable evidence that every weak point has been found, but it is undoubtedly a useful adjunct to the search for such points. It is for consideration whether the same effort employed in strain gauge exploration, and greater volume of detailed testing, would pay better dividends than a complete wing test.

Pressure Cabin Testing

The pressure cabin presents serious testing problems. One of the principal loading actions—namely the internal pressure—is known precisely, but the local external air pressures, which may be appreciable in high speed aeroplanes, somewhat complicate the matter. It is the application of the loads which raises the real problems. The conduct of detailed tests—equivalent to the testing of a wing spar—is by no means easy. One is usually concerned with curved panels, which are subjected to longitudinal stress, hoop stress, and possibly shear stress. It is obviously very difficult to reproduce, in a fatigue test, this kind of loading.

Difficulties of detailed testing have led to tests on partial cabin structures (*e.g.* complete nose sections) and more recently to tests on complete cabins with wings attached. In both cases the cabin is tested under water loading, partly for safety's sake, and partly to limit the destruction so that the origin of failures can be found and the cabin repaired for further testing.

These advantages of underwater testing are to be weighed against two drawbacks. Firstly, it is most important to know whether cracks which form are of the safe or "explosive" variety. But there is no proof, at present, that a safe crack in an underwater test might not be of the catastrophic variety if it occurred in the air. Secondly, general testing evidence of aluminium alloys in water and in air suggests that, even in relatively pure water, corrosion accelerates fatigue in comparison with tests in air. In this connection, however, the fact that the aeroplane itself is alternatively wet and dry must be remembered.

The test on a single cabin also raises problems similar to those of the wing test. If it is to be relied on to find all the potential weak points, or if it is the sole evidence available for purposes of establishing safe life, it is necessary to proceed to a very large number of loading cycles in order to cover possible scatter.

In general, I feel that testing of complete cabins is necessary for the present time. The great importance of a most careful examination of the testing problem is recognised, however, and the necessity for research into methods of test with the object of finding methods which would provide more information for a given expenditure of effort.

Tailplanes

Lack of time prevents inclusion of any discussion of the tailplane problem, but absence of discussion does not mean there is no problem. At the moment it is less fully understood than is the case for wings and cabin, and exploratory work is urgently needed.

Comments on the Present Situation

In my view the present state of affairs which necessitates fixing safe lives for principal components is totally unsatisfactory. There is first the expensive test programme involving a complete wing and cabin, together with several full-scale components. These tests inevitably occupy much time. If the aeroplane concerned is made in small numbers, the testing costs are prohibitive. Another problem concerns the development of a type by occasional changes, such as the increase of span or fuselage size. Whereas in the past such a change required little structural investigation, with fatigue in mind major structural tests become necessary.

Having undertaken the test programme and established safe lives of main components, the operator is then faced with the serious disadvantage of grounding aircraft periodically for replacements to be fitted.

There is finally the realisation that, in spite of the large factors on life, it is all too easy to be in error. What then is to be done to improve the situation? It is as well to consider the matter under two headings—the immediate future and the long term future.

Immediate Future

In aircraft, in which failure under fatigue loads is potentially catastrophic, there seems little escape from the full testing programme. The main avenue for improvement lies in increasing our knowledge so as to avoid imposing any unnecessary margins and yet making completely certain of the safety of the aeroplane. Among the various possibilities the following stand out:—

(*a*) Research work to obtain a reliable cumulative damage rule.

(*b*) Carrying out sufficient tests on various materials and forms of construction to obtain more data on scatter.

(*c*) Routine use of counting accelerometers in each aircraft type and route. It may also become possible to carry a small counting accelerometer in each aeroplane (*e.g.* the R.A.E. "Fatigue Meter.")

(*d*) Research to determine the validity of results of underwater pressure cabin testing (relative to tests in air).

(*e*) Development of methods of tests on small sections of pressure cabins.

Longer Term Development

There are broadly three ways in which more fundamental improvement may be sought. One is to improve materials so as to increase their fatigue characteristics and to reduce scatter. The second is to employ detailed design which improves fatigue life. The third is to use structural arrangement and stress levels which avoid fatigue failure being catastrophic.

It seems to be quite possible that if materials were developed with special attention to their fatigue properties instead of attention to static strength properties, some improvement might accrue. Some reduction of

static strength would be well worth accepting if fatigue properties benefited. Tests on materials made to the same specification but by different suppliers have shown average lives in the ratio of 2:1. This suggests that, if certain of the specification tolerances were reduced, the material properties would improve.

So far as scatter is concerned, reduction of scatter could be just as beneficial as increase of average life. Again, there is some evidence that the relative scatter of current materials varies considerably.

The mechanism of fatigue is not sufficiently understood for it to be possible to forecast fatigue properties from a knowledge of the material specification. This being so, it seems necessary to find by trial and error the ingredients and manufacturing treatments which would improve the fatigue properties. Possibly a thorough exploration of materials made to current specifications would be a useful start.

In this connection it is of little use comparing fatigue properties of different materials by the conventional smooth bar test specimens. The aircraft designer needs to know whether material *A* is better than *B* when made up into typical bolted and riveted joints. Hence the test specimen must be reasonably representative of forms of construction.

The aircraft constructor has various detailed methods at his disposal for improving fatigue life. There are the well-known ones of reducing stress concentrations by avoidance of sharp corners, smooth gradation of cross-sectional areas, and so on. Although such principles are so well established, it is surprising how often the most elementary errors creep in and the importance of good detailed design cannot be over emphasised. It might be well to introduce a routine procedure into the Drawing Office system to check for adequacy of fillets, and so on.

Workshop errors can reduce fatigue life just as seriously, if not more so, than bad design. A spar has been known to fail under test at a fraction of its normal life in consequence of the stress concentration caused by a tool mark at a bolt hole. A burr on a bolt can cause a deadly scratch in the bolt hole. Since many such errors are concealed as they occur, inspection will not deal with them all. The man on the bench or in the assembly shop must himself understand the importance of the utmost care.

Some attention has been paid to various fabrication methods intended to improve fatigue life. Some of these are based on the principle that fatigue cracks usually start at the surface of the metal, and if the surface is in compression the onset of cracking is delayed. Laboratory tests have shown that by employing interference fit bolts or bushes, with just the right degree of over-size, substantial (5 to 10 times) increase of life may be obtained. Evidence is lacking whether this improvement would be achieved under a mixed spectrum of loads. Shot peening is also known to improve life. I am, however, very doubtful about the wisdom of relying on methods which put an even greater emphasis on workshop control for their success. Generally speaking, the more highly "tuned" the system is by which we seek success, the greater is the loss if an error occurs. On the whole, while I believe that all efforts should be made to avoid bad practices, I think it should be assumed that errors will occur sooner or later, and try to use structures which take errors in their stride. I am convinced that the use of reasonable stress levels is the only certain way to succeed.

This leads to a discussion of structural arrangement and stress levels. Structures can be classed in two ways:—

A. Those with sufficiently low stress level that their lives are well beyond the operational life.

B. Those with stress levels such that the lives are (or may be) within the operated life.

and

1. Those which give adequate warning of serious failure by virtue of seeable cracks which grow slowly.
2. Those which fail catastrophically without adequate warning.

It is clear from past events that some modern aeroplane structures, both wings and pressure cabins, fall in Class *B*2. I would like to see them all in Class *A*1.

Bearing in mind the very serious penalties which accrue from short life, it is for serious consideration whether it would not be preferable to increase the dimensions of important members to such a point that the lives would be well beyond anything likely to be reached operationally.

Suppose that an average life for a spar is about 30,000 hours. If this average life could be raised fivefold to give 150,000 hours, then even with generous allowance for scatter, there would be little doubt about the safety in ordinary operational life. To achieve this means reducing stresses by about 35 per cent. In other words, an increase of the lower spar size by about 50 per cent. or a little more would achieve the results. In practice this would not necessarily mean as much as 50 per cent. increase of spar flange weight, as all sections of a spar would not usually be critical.

If a heavier spar were used, static strength considerations would no longer be important in design, so a material with lower static ultimate properties could be used. It is likely that such materials would be better in fatigue. Thus, in the outcome perhaps a 25 per cent. or 30 per cent. increase in the weight of the lower flange of the spar would put the design out of fatigue troubles.

Discussing structural arrangement, Rhode[1] points out that redundancy of the structure in the ordinary sense is not in itself sufficient. What is wanted is a structural arrangement such that the cracks which occur will be readily observable before causing appreciable reduction in static strength. Slow growth of cracks is an obviously important contribution. Structure in which the load bearing part is external rather than internal is preferable from an inspection point of view (*i.e.* the heavy skin in contrast to the heavy spar construction). The loss of static strength for a given area of crack has not been fully examined. Rhode[1] showed results of one set of tests on a heavy flange in which roughly a 50 per cent. reduction of static strength was caused by a crack extending over 10 per cent. of the cross section.

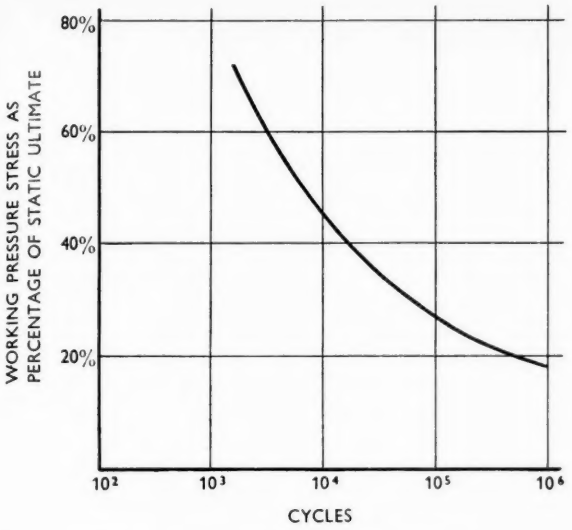


FIGURE 7. Typical *S-n* curve for pressure cabin.

The inference to be drawn from practical experience is that structures with heavy skins and light spars gave adequate warning before serious loss of strength, while single and twin spar structures with light skin do not. While the latter is clearly true, it is uncertain whether the former is always the case. It seems possible that if a structure operates at high stress levels, then even with a heavy skin construction, rapid crack growth could occur, and loss of static strength for a small crack might be large. Research is necessary into these matters.

In the case of the pressure cabin, when the differential pressure is low—say 4 lb./in.²—the use of skin of minimum practicable gauge ensures a low general stress level. With a differential pressure of 8 lb./in.², a diameter of 10 feet, and a skin thickness of 0·028 in., the hoop stress is 17,200 lb./in.². The net area stress at riveted seams away from the large cut-outs might be, say, 23,000 lb./in.² or 35 per cent. of ultimate static strength. Reference to Fig. 7 shows a corresponding average life of 30,000 cycles or a safe life of about 10,000 pressurisations. This suggests at first glance that there is no serious problem. However, there are inevitably cut-outs in the skin to accommodate windows, doors, and so on, and these, without reinforcement, can double, treble, or quadruple, the stresses. For instance, if stresses near the cut-out rise to as little as 50 per cent. above the mean level, the mean life falls to about 5,000 cycles or a safe life of about 1,700 pressurisations. On the other hand, if stresses away from cut-outs are kept to a low level—say 12,000 lb./in.², or about 20 per cent. of ultimate—a stress concentration of 50 per cent. above the average level would not apparently lead to an unacceptably low life.

To maintain stresses near the cut-outs to the level obtaining in the main skin requires reinforcement applied in a skilful manner. The stiffness of the reinforcement must be just right, as too stiff a reinforcement induces high stresses in the skin immediately adjacent to it.

The effects of damage during construction or operation must also be remembered. In a recent lecture, Hitchcock[10] says

> " . . . it should be conservatively assumed that punctures, tears, cracks, and other damage, are inevitable during the service life of an aeroplane, even though supreme effort has been made to keep them to a minimum."

British experience supports this view. A crack, whatever the cause, induces enormously high stress concentration.

As in the case of the wing, it seems possible that the rate of growth of the crack once formed may be related to the general stress level. It is clear from the Comet tests that rate of growth can be anything from very slow inspectable cracks, up to what is virtually instantaneous catastrophic tearing. Certain American aeroplanes, which employ low stress levels (away from the cut-outs) of the order of 8,000 to 12,000 lb./in.² are known to have had cracks in pressure cabins with non-catastrophic results. The matter is somewhat confused because low stresses have usually gone hand-in-hand with low pressure, and hence a lower degree of stored energy in the contained air. What is needed is a controlled experiment in which stress level is varied while internal energy is kept constant, and in which the energy is varied while the stress level is kept constant. I feel convinced, however, that we should conclude that safe design is primarily dependent on the use of conservatively low values of stress, possibly not exceeding 12,000 lb./in.².

Conclusions

For the immediate future we are driven to full-scale and *ad hoc* testing of wings and cabins, and probably tailplanes. Coupled with increasing use of counting accelerometers and research into such matters as cumulative damage and methods of test, a position will be reached where a safe life is truly safe.

I believe however that the ultimate solution is to obtain a sufficient understanding of the problem that it will be possible to design structures, the fatigue failure of which would be well beyond the operational life, and in which, if cracks do occur the failure will be non-catastrophic in character. Until this goal is reached, no one—the designer, the operator, the research organisations, and the airworthiness authority—should rest content.

Acknowledgments

I am indebted to the Board for permission to read this lecture but the opinions expressed should not be taken as other than personal. I am specially grateful to two colleagues, J. Keri Williams and A. P. Kennedy, as this paper could not have been written had I not had the advantage of frequent discussion with them, and a knowledge of their work on fatigue problems.

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N. E. ROWE (*Fellow*). *Contributed*: Mr. Tye has directly and by implication brought out many gaps in our knowledge on the subject of airframe fatigue. These have been obtaining growing recognition over the past three to five years, but they are now sharply emphasised by their enormous effect on the testing programme of new types of aircraft, especially civil aircraft. The idea of continuing to test complete aeroplanes for fatigue is vaguely repugnant to engineers because it reflects vast uncertainties which should not exist in good design.

Running through the latter part of the lecture is the scatter motif raising 10 to one uncertainties and hence the most cautious attitude to the results of the best devised tests on the ground. The lecturer himself was uncertain how far this cautious attitude was justified by practical experience; he instanced the case of the two wing failures of Doves operating in Australia in which the hours of operation under given conditions before failure were almost identical. The lack of scatter was also apparent, I thought, in the evidence on the Viking spar failure. Practical evidence on this aspect is clearly necessary because the scatter concept carried into practice can result in possibly unnecessary diseconomies in the use of material. One gathers that Counting Accelerometers are now being used on Doves operating in Australia in conditions similar to those in which the early spar failures occurred, and the results obtained from these should be most illuminating. Relevant comment on this point is also contained in the report of the Court of Enquiry into the accidents to the Comets, where the effect of preloading to high loads was suggested as possibly explaining the observed scatter in this case.

The broad correlation between the effect of gusts and fatigue seems to be fairly clear on structures which are primarily affected by these loads. Presumably if one could obtain complete alleviation of gust effects then the structures of aerodynamic lifting surfaces might have an indefinite life unless small-scale vibration also enters into the fatigue effects and I personally feel that this cannot yet be ruled out. A good deal of work was done on gust alleviation when the Brabazon was being developed, but major difficulties were found and I understand that no work on these lines is now being done. In view of the great practical advantages which would come from effective gust alleviation, I suggest that research work on this subject should be pursued on a high priority.

The lecturer by implication returns to the simple lesson we have all learned long ago—that stress concentration should be avoided. This is not at all easy in the shell structures used in aircraft work; the ideal pressure cabin would have no cut-outs at all. Presumably then the entry doors would be through the nose for the crew and through the rear end of the fuselage for passengers, these holes then being closed by pressure type doors not involving holes in the skin. Windows having been discarded, more weight and money might be needed for the alleviation of boredom, e.g. the lounge-bar so popular on Stratocruisers. We may come to this; in fact we have already come to this on our tube trains where although we have windows no-one attempts to look out except at stations, because there is nothing to see.

The problem of materials is obviously a major one and here the need seems to be for an understanding of the physical nature of the action of repeated stress in aluminium alloys. This sounds like asking for the moon, except that one heard very interesting results quoted in Sir Arnold Hall's recent Brancker Memorial Lecture to the Institute of Transport. For the first time physical effects were being observed which could be related to fatigue, and this may convey tremendous hope for the future.

Recent Developments in the Hydrodynamic Design of Flying-Boats*

by

J. H. PATERSON, G.I.Mech.E., Grad.R.Ae.S.

Introduction

During the past few years numerous developments in the hydrodynamic design of flying-boats have been brought about mainly by systematic model research. Although Germany deserves the credit for initiating research on the forces on planing plates and Vee wedges, we are indebted to various establishments in the U.S.A. for the multiplicity of data on both flying-boats and simple planing surfaces, which are now available.

Notation

B or b	maximum beam at chine, feet
L	overall length of planing-bottom, measured parallel to the forebody keel at step, from the keel-chine intersection at the bow to the rear step heel, feet
l_f	forebody length, measured parallel to the forebody keel at step, from the keel chine intersection at the bow to the step centroid, feet
l_a	afterbody length, measured parallel to the forebody keel at step, from the step centroid to the rear step heel, feet
L/b	overall length-to-beam ratio
l_f/b	forebody length-to-beam ratio
l_a/l_f	afterbody length-to-forebody length ratio
Δ_0, W	all up weight, lb.
Δ	load-on-water = A.U.W. – wing lift, lb.
$C_{\Delta 0}$	static beam loading coefficient $= \dfrac{\Delta_0}{w b^3}$
$C_{\Delta 0}\left(\dfrac{b}{l_f}\right)^2$	forebody loading coefficient $= \dfrac{\Delta_0}{w l_f^2 b}$
w	mass density of water, lb./cu. ft.
T	thrust, lb.
R	drag, lb.
$C_{L\,T.O.}$	wing lift coefficient at take-off incidence
η	elevator angle, degrees
τ	attitude or trim angle of forebody keel to undisturbed water surface, degrees
β	deadrise angle measured between the tangent to the planing bottom at the keel and the horizontal, degrees
h	depth of main step, feet
σ	sternpost angle, measured between the forebody keel at step and a line joining the main step heel to the rear step heel, degrees
θ	afterbody angle, measured between the forebody keel at step and the afterbody keel, degrees.
Warp	the rate of change of deadrise with distance from the step, deg./beam

Geometrical parameters are illustrated in Fig. 1.

*Based on a paper which won First Prize at the Isle of Wight Branch Lecture Competition in 1954. The opinions expressed are the author's. Mr. Paterson is now with A. V. Roe (Canada) Ltd.

Historical Survey

Until about 10 years ago the physical size of a flying-boat's planing bottom was governed mainly by a beam loading coefficient of 1·0 and a length-to-beam ratio of 6. In fact these two values may be said to typify the vast majority of flying-boats constructed between the early 1930's and the late 40's, as illustrated by Fig. 2. This shows the variation of beam loading coefficient, $C_{\Delta 0}$, with forebody length to beam ratio. The points shown fall into three distinct groups. At the bottom left hand corner are three "Short" hulls, the Calcutta, Kent, and Singapore III. The fourth point is the Consolidated Catalina; the average beam loading is 0·35.

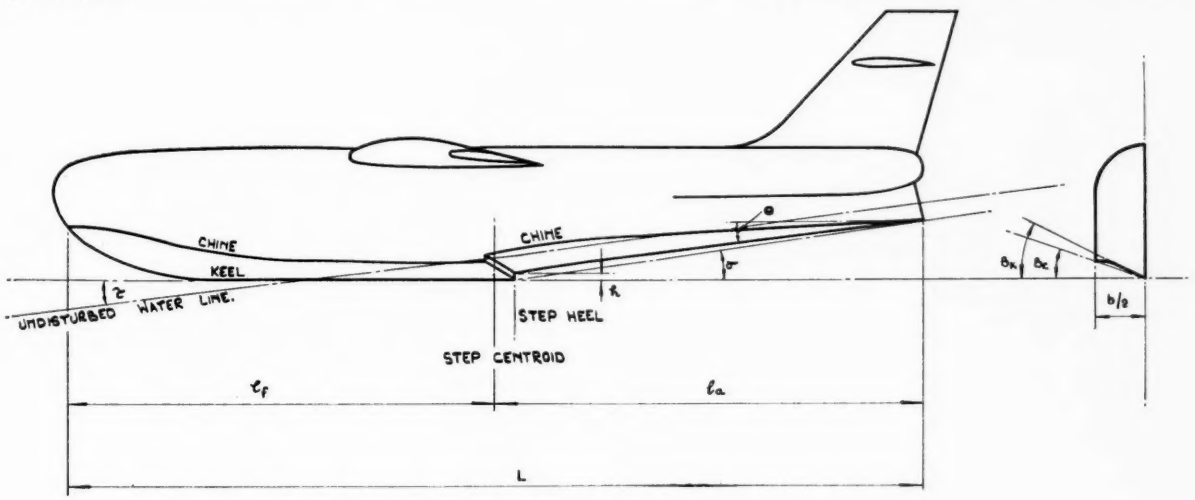

FIGURE 1. Geometrical notation.

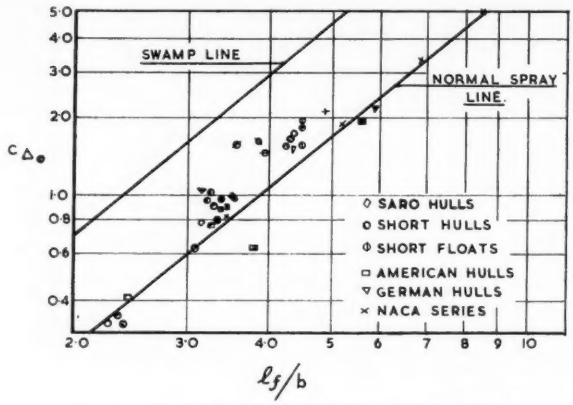

FIGURE 2. Variation of beam loading with forebody length-to-beam ratio.

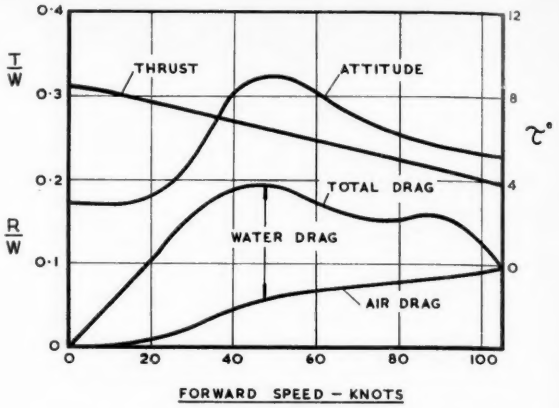

FIGURE 3. Thrust, drag and keel attitude during take-off.

The second group with beam loadings of approximately 1·0 includes all except the most recent American flying-boats; examples in this group are: the Short "G" class, Empire, Sunderland III, Seaford, Solent, Sealand I, Shetland, the Saro SR.A1 and Princess, the Heinkel HE.57, the Martin Mars, the Mariner, and the Boeing Sea Ranger. The exception which proves the above rule is the Blohm and Voss B.V.222 which had a beam loading of just over 2·0 and an overall length/beam ratio of 8·75, the forebody length/beam ratio being 5·9.

The third group of points is data appertaining exclusively to the floats of twin float seaplanes. It is interesting to note that while floats were being designed to beam loadings of between 1·5 and 2·0 and length/beam ratios of 8, hulls were restricted to beam loadings appreciably lower than 1·0 and length/beam ratios not greater than 6·0.

The desire to increase the load carrying capacity of flying-boats without unduly penalising the hydrodynamic behaviour led to systematic research into the effects of varying the geometrical proportions of hulls on their resistance, stability, and seaworthiness characteristics. The results of these researches indicated that by increasing the length-to-beam ratio while maintaining a constant value of forebody loading coefficient, $C_{\Delta_0}(b/l_f)^2$, considerably higher values of C_{Δ_0} were possible.

Effect of Planing Bottom Geometry on Hull Drag

The following is a brief outline of how the water drag of a flying-boat is affected by changes in the planing bottom geometry. For those who may not be conversant with the mechanics of flying-boat take-off behaviour, the following explanation may help.

During take-off, a flying-boat passes through two distinct regimes, namely the displacement or low speed region, and the planing region. In the former, the hull is supported mainly by buoyancy forces while at high speeds normal pressures on the hull bottom provide the required water lift. As speed increases the planing lift provides an increasing proportion of the total water lift, so that the hull draught decreases. This is accentuated by the wing lift which, as speed increases reduces the total water lift required.

At rest, the centre of buoyancy is vertically below the centre of gravity, whereas in motion, the planing forces present, having a centre of pressure forward of the centre of buoyancy, cause the hull to trim up. This tendency is increased by the afterbody which sinks into the trough generated by the forebody. As speed increases and the hull rises out of the water, the centre of pressure moves aft and, if the trim was held fixed, would finally pass behind the centre of gravity, so that in practice the hull trims down with further increase in speed. Thus we have the characteristic "humped" trim curve illustrated in Fig. 3.

At low speeds the water drag is almost entirely due to skin friction but as speed increases there is a rapid rise in the total water drag due to wave making. The region of rapid drag increase corresponds to the increase in trim already mentioned, the wave-making drag varying approximately as speed to the power of six.

At very high speeds the hull draught is small, as is the wetted area, so that the skin friction component of the total water drag is also small. The major component is the horizontal component of the planing lift, *i.e.* planing drag is approximately equal to $\Delta \tan \tau$, where Δ equals the load-on-water and τ is the mean inclination of the wetted region of the planing bottom. The friction drag is given by $R_F = \frac{1}{2}\rho S_F V^2 . C_f$ where S_F is the effective wetted area and C_f is a friction drag coefficient varying with speed and effective wetted length of planing bottom. In the transition, or hump, region between the pure displacement and pure planing conditions, the

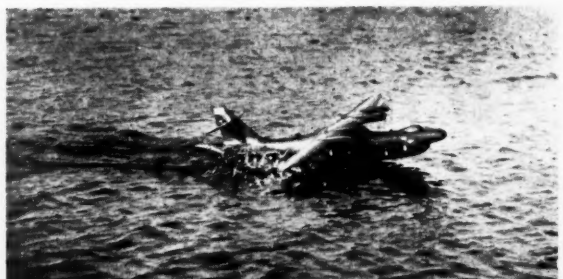

FIGURE 4. Model of a high length-to-beam ratio flying-boat taxying at "hump" speed.

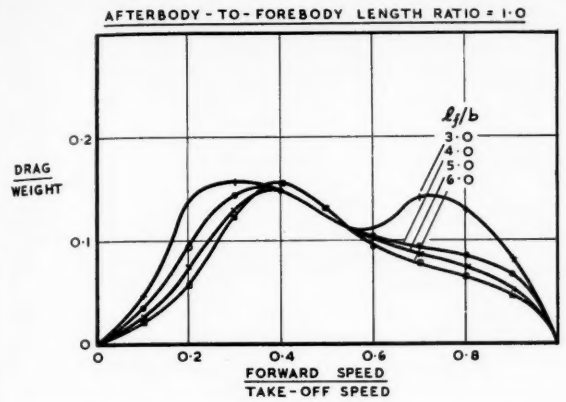

FIGURE 5. Effect of forebody length-to-beam ratio on drag.

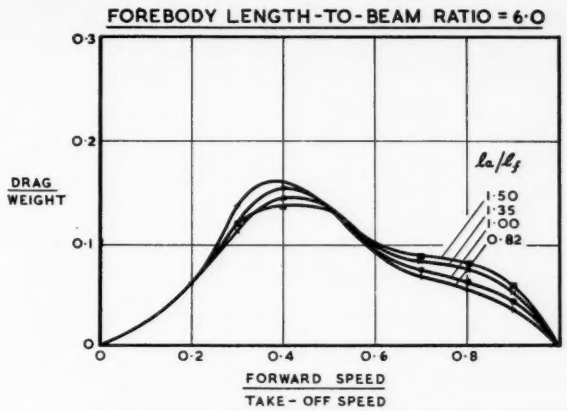

FIGURE 6. Effect of afterbody-to-forebody length ratio on drag.

water drag consists of planing, friction and residual components, the last named being due mainly to wave making. Thus the transition drag exceeds the pure planing drag extended to lower speeds by the residual component but is less than the pure displacement drag curve extended to higher speeds. A typical take-off drag curve, including the air drag component, is shown in Fig. 3.

Near take-off speed a second drag "hump" may occur due to increased friction drag caused by a thin film of water tending to cling to the planing bottom. This is sometimes accentuated by a thin skin of water attaching itself to the afterbody.

These two humps are points of minimum acceleration and their relationship to the thrust available at the respective speeds constitutes criteria of the take-off performance, the accepted minimum acceleration being 0·05g.

Figure 4 shows a model of a modern flying-boat taxying at hump speed in the open sea.

The water drag curves shown in the following figures are appropriate to a hypothetical flying-boat having an all-up weight of 135,000 lb., a wing loading of 62·5 lb./ft.^{2}, a C_L at take-off of 1·7 and a static forebody loading coefficient $C_{\Delta 0}(b/l_f)^2$ of 0·09. The curves are plotted in the non-dimensional form of R/W versus $V/V_{T.O.}$ and do not include the air drag of the hulls.

Figure 5 shows the effect of increasing the forebody length-to-beam ratio from 3 to 6 while the other geometrical parameters remain fixed. Except in the hump region, where there is virtually no effect, the drag is considerably reduced by increasing the length to beam ratio; this drag reduction is due to the change in the effective aspect ratio of the planing bottom wetted areas.

Figure 6 shows the effect on drag of increasing the afterbody to forebody length ratio from 0·82 to 1·5 while the forebody length/beam ratio remains constant at 6.

In the hump region drag decreases with increasing (l_a/l_f) ratio but at high speeds the reverse is true, the reason being that in the hump speed region the longer afterbody depresses the trim which correspondingly reduces the drag; the longer afterbody, however, continues to contact the water surface at speeds higher than those at which the short one rises clear and thus increases the hull drag at high speeds.

Figure 7 shows the effect on drag caused by increasing the forebody deadrise in the step region from 20° to 35°. At low speeds there is virtually no effect, but above about 0·4 of take-off speed drag increases rapidly with increasing deadrise. To provide equal lift at a given speed, hulls with higher deadrise angles require larger wetted areas and thus have higher friction drag components. Since buoyancy provides the greater portion of the total water lift at low speeds, the effect of increased deadrise angles is not appreciable until relatively high speeds are achieved.

Although radical changes in the sternpost angle required on a flying-boat have not occurred during recent years the importance of this angle, particularly on modern hulls having long afterbodies, warrants a brief mention of its effect on hull drag.

A change in sternpost angle or, other things being equal, a change in afterbody angle, causes a change of equal amount in the hump trim of the flying-boat. This trim change causes a proportional change in the planing drag, which equals the product of the load on water and the difference between the tangents of the respective trim angles.

Long hulls and, in particular, ones having high afterbody to forebody length ratios, *i.e.* greater than 1·0, require sternpost angles of about 8° or larger, smaller

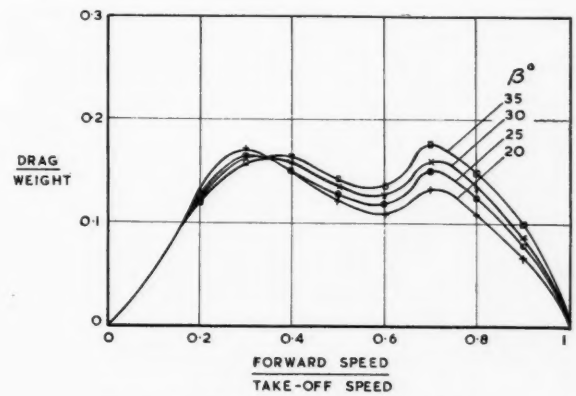

FIGURE 7. Effect of deadrise angle on drag.

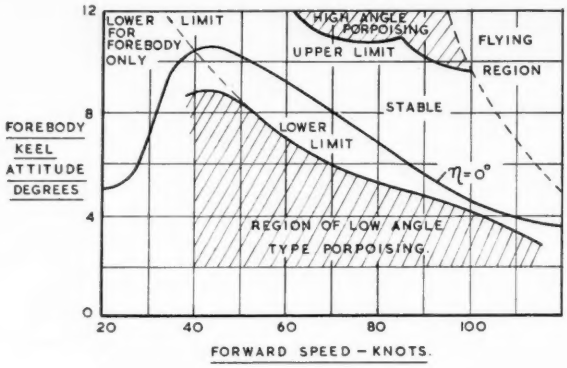

FIGURE 8. Typical take-off stability diagram.

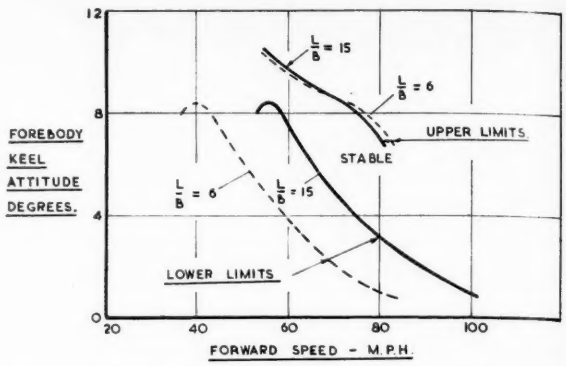

FIGURE 9. Effect of length-to-beam ratio on take-off stability.

angles tend to cause afterbody sticking and may lead to unacceptable longitudinal stability characteristics.

The foregoing are the main parameters affecting hull drag, although the step depth and form, afterbody deadrise and so on, have second order effects.

Longitudinal Stability

The longitudinal instability of flying-boats is commonly called "porpoising," since it often resembles the characteristic motion of that creature. There are a number of variants, skipping, pattering, low angle porpoising and so on.

All these in common, are unstable non-conservative coupled motions in pitch and heave sustained by the engine thrust during take-off and the drag during landing, an unstable motion being arbitrarily defined as a sustained oscillation having a total amplitude of pitch greater than 2°.

The two main types of instability which will be considered here are known as low angle and high angle porpoising. Fig. 8 indicates the regions in which this instability may be found. Low angle porpoising is mainly a function of forebody design though afterbody damping suppresses the lower limit in the hump region. Compare the dotted line, which is the lower stability limit for a forebody alone with the solid line for a complete hull.

The severity of the instability increases with the degree of penetration of the lower unstable region and is worse at high speed than in the hump region. It is possible to accelerate through the hump unstable region at the expense of only a mild rocking, but nosing into the lower limit at high speeds can be catastrophic. The upper limit conforms very closely to those combinations of trim and speed which bring the afterbody into contact with the forebody wake.

The porpoising which occurs when the upper limit is penetrated does not become rapidly worse with degree of penetration, but the trims are so high that the aircraft may be thrown clear of the water and stall-on again. When this happens intermittently the motion is distinguished by calling it skipping. It is found in both take-off and landing but more often in the latter.

The effect of increasing the length beam ratio from 6 to 15 on the range of stable trims available for take-off is shown in Fig. 9. This reduction in the stable trim range constituted a serious disadvantage to the introduction of long narrow hulls, with their attendant improved sea-worthiness and drag characteristics.

The problem gave rise to a reconsideration of the basic aspects of flying-boat design practice. It was realised many years ago that satisfactory lower limit stability could only be achieved by making the buttock lines in the step region approximate as closely as possible to straight lines, and designers in the past obtained the desired result by making the forebody deadrise constant over a region of about 1·5 beam lengths from the step; this became known as the "forebody flat." The advent of the long forebody resulted in some further thought regarding this matter and it became obvious that it was unnecessary to maintain constant deadrise to achieve the desired effect; by increasing the deadrise forward of the step at a uniform rate, *i.e.* warping the forebody, satisfactory buttock lines were obtained and it was found that the stability characteristics of long hulls were improved.

Figure 10 shows that the effect of increasing the linear rate of warp is to lower progressively the lower limit. The rate of warp required to obtain satisfactory stability increases with increasing length/beam ratio, and although no definite rule can be laid down a rough guide is given by:

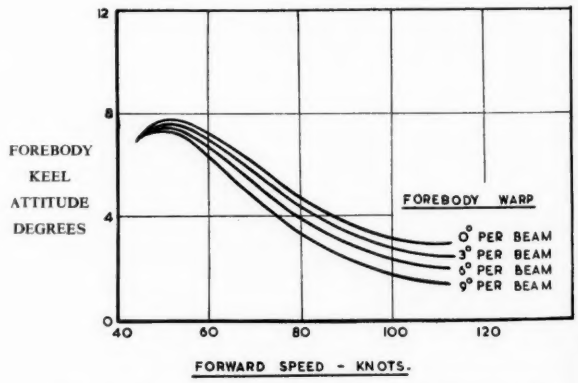

FIGURE 10. Effect of forebody warp on the lower limit of stability.

Rate of warp in degrees per beam = 1·5 × forebody length to beam ratio.

The stability of long narrow hulls may be improved considerably by employing an afterbody of greater length than the forebody and, for flying-boats intended to operate in severe sea conditions, a long afterbody is essential. An afterbody to forebody length ratio of approximately 1·25 to 1·35 will normally provide satisfactory stability characteristics, but the final choice of this ratio must be a compromise between the requirements of drag, stability and impact accelerations and, of course, must be considered in conjunction with other geometrical proportions such as sternpost angle and afterbody deadrise.

Spray Characteristics

The next item of fundamental importance is the spray generated by the forebody, which determines to a great extent the height at which the engines must be located in order that the spray will not impinge on the blades of the propellers.

Two forms of spray emanate from the forebody, namely "ribbon" and "blister" spray. The former travels outboard almost normal to the hull centreline and remains comparatively low. The blister spray, however, travels backwards and outboards and rises to quite considerable heights; the height increases with speed, but since the origin of the spray also moves aft with speed, the maximum height of the spray blister occurs aft of the plane of the propellers. Fig. 11 shows a typical low-speed spray pattern on a full scale aircraft.

Referring to Fig. 2 again, the four x's shown are a N.A.C.A. model series and it will be observed that they lie along a straight line. All points on this, or parallel lines, have constant forebody loading, $C_{\Delta_0}(b/l_f)^2$, which signifies similar spray height characteristics. The lines marked "Normal spray" and "Swamp line" have forebody loadings of 0·067 and 0·18 respectively, which indicates the deterioration in spray cleanliness with increase of forebody loading coefficient. The N.A.C.A. hull series have length-to-beam ratios of 6, 9, 12 and 15, and corresponding beam loadings of 0·8, 1·8, 3·2 and 5·0, respectively. These high C_{Δ_0} values are achieved without deterioration in spray characteristics, as illustrated by Fig. 12. This shows that while forebody loading is held constant, the beam loading may be increased considerably and slight improvement in spray characteristics may be obtained by increasing the forebody length-to-beam ratio.

FIGURE 11. Typical low-speed spray pattern on a full-scale aircraft—the Saunders-Roe Princess.

Warping the forebody also reduces the height of the blister spray in the plane of the propellers, but tends to increase the height farther aft in the wing flap region. Fortunately this tendency is not very marked and the advantage gained in propeller tip clearance more than outweighs the slight deterioration farther aft.

Behaviour in Waves

Flying-boat behaviour in waves can be appreciably improved by increasing the length-to-beam ratio, as illustrated by Fig. 13. This shows the maximum vertical accelerations sustained by flying-boats having length/beam ratios of 6 and 15 during landings in 4 ft. waves of various lengths. Both aircraft sustain peak accelerations in wave lengths of about 1·5 times the planing bottom length.

However, increasing the length/beam ratio is not as effective as increasing the afterbody/forebody length ratio, as indicated by Fig. 14. This shows the variation of the peak vertical acceleration with l_a/l_f ratio and indicates that the acceleration progressively decreases with increase in this ratio.

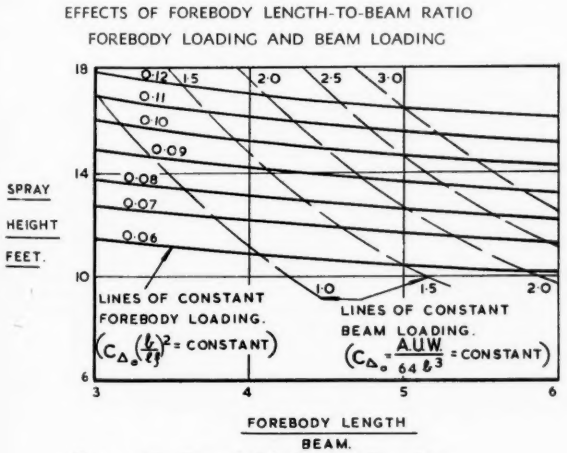

FIGURE 12. Spray height in propeller plane.

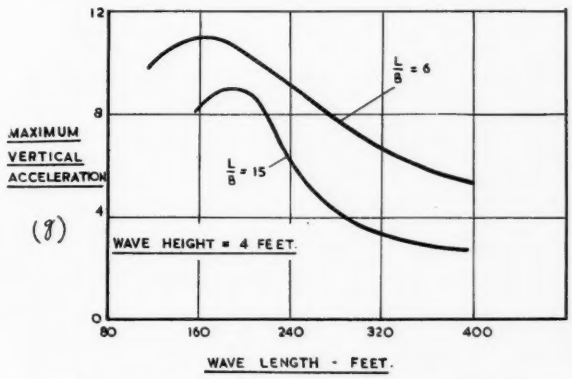

FIGURE 13. Effect of length-to-beam ratio on maximum vertical acceleration during landing.

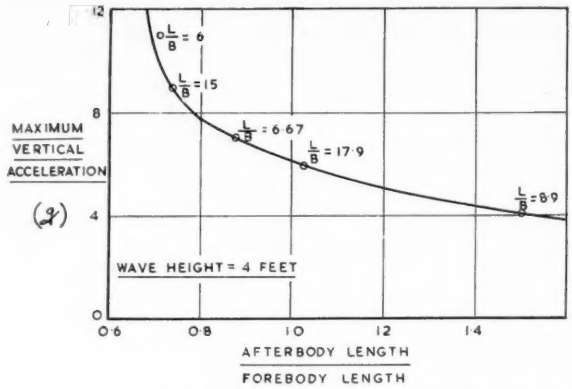

FIGURE 14. Effect of afterbody-to-forebody length ratio on maximum vertical landing acceleration in critical wavelengths.

Note that the hull of length-to-beam ratio equal to 15 and afterbody-to-forebody ratio of 0·74 sustained an acceleration of 9*g*, whereas the hull of length-to-beam ratio equal to 8·9 and afterbody-to-forebody length ratio of 1·5 sustained an acceleration of only 4·2*g*.

It will be observed that the rate of reduction in peak acceleration decreases as afterbody/forebody length ratio increases; thus since hull drag increases with high values of this ratio, a very satisfactory compromise is achieved by using an afterbody/forebody length ratio of 1·25 to 1·3.

The impact loads and pressures sustained by flying-boats when landing are closely related to the planing-bottom deadrise angles, thus, warping the forebody results in a more gradual build-up of the load than that obtaining with conventional flying-boats having a "forebody flat" or constant deadrise section.

Figure 15 shows a moderately high length-to-beam ratio hull model landing in an 8 ft. swell of critical length (*i.e.* 1·5 × planing bottom length); the same model is shown landing in a complex sea consisting of an 8 ft. cross-sea superimposed on a 12 ft. swell of critical length, in Fig. 16. (These sea conditions are created by the oscillating hinged paddle type wavemakers fitted in the Saunders-Roe Free Launching Tank). A hull of conventional length-to-beam ratio would not be capable of landing in such seas and in less severe seas has a smaller range of safe landing attitudes.

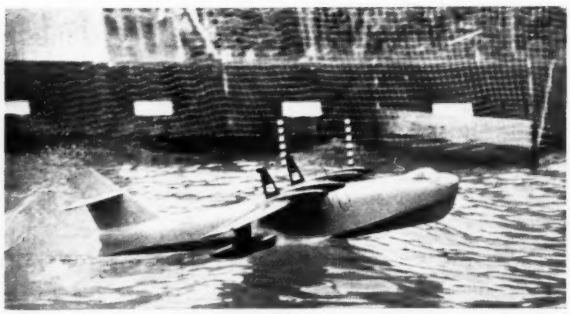

FIGURE 15. Model of a high length-to-beam ratio flying-boat landing in an 8 feet high swell of critical length.

Manoeuvrability of Flying-Boats

The final aspect of flying-boat behaviour discussed is the manoeuvrability on the water. For satisfactory flying-boat operation from restricted waterways the aircraft must be able to accomplish turns of small diameter.

The majority of existing aircraft rely on asymmetric thrust to provide turning moments required for manoeuvring. Fig. 17, illustrates the effect of various methods of using the engines of a four-engined flying-boat on the turning radii attainable.

Curve *A* shows the variation with speed of the minimum turning radii attainable, while using differential forward thrust only. Curve *B* shows the radii of turn attainable by using reverse thrust on the inner engines to reduce forward speed, *i.e.* the inner engines are used as a brake and do not contribute to the turning moments available, while the outer engines provide differential forward thrust. By employing reverse thrust on one inner engine only, the radii of turn can be appreciably reduced, curve *C*.

Curve *D* shows the worst case from the turning point of view, which results from using both outer engines as a brake and relying on the inner engines to provide differential forward thrust.

The use of reverse thrust on one outer engine only results in the turning radii of curve *E*, while curve *F* is the case when both the outer and the inner engines are used to provide reverse thrust.

These curves indicate that it is undesirable to use reverse thrust purely as a brake during turning manoeuvres, although it is beneficial to other manoeuvres, *e.g.* landing and approaching the buoy. The curves further indicate that the use of reverse thrust on an outer, rather than an inner, engine does not significantly reduce the radius of turn except at speeds greater than about 15 knots.

Water rudders and hydroflaps may also be used to improve the performance, but since both these devices derive their effectiveness from the forward speed of the craft they are of little use for very low speed manoeuvring, *e.g.* in approaching the buoy for mooring up.

Hydroflaps, however, have proved very effective for manoeuvring at speeds in excess of 20 knots when the asymmetric thrust available from the engines falls off, due to the increase in hull drag as the hump speed is approached. There is every reason to believe that a

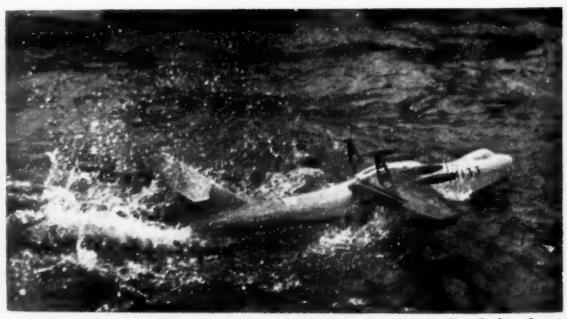

FIGURE 16. Model of a high length-to-beam ratio flying-boat landing in a complex sea—8 feet high cross-sea superimposed on 12 feet high swell.

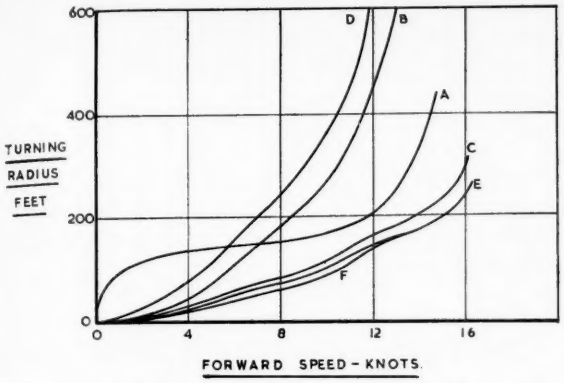

FIGURE 17. Variation of turning radius with speed for various propeller thrust conditions.

simple water rudder, properly designed, would be equally effective at these speeds.

Figure 18 compares the turning moments available from a water rudder of 24 sq. ft. area, hydroflaps of the same area, and the asymmetric thrust moments available from the engine of a multi-engined flying-boat.

This shows that the hydroflap deflected through 65° is less efficient than the simple rudder deflected through 15°, and that without using reverse thrust the engine moment available is greater than either rudder or flap at speeds below 18 knots. Reverse thrust increases this figure to 21 knots. Of course, a larger rudder area or an increased deflection alters these figures, *e.g.* a rudder angle of 30° reduces the former figure to about 5 knots and the latter to 11 knots. The lines at the top of the graph show the engine moments available during an emergency or accelerated runs.

Hydroflaps have an advantage over the simple rudder, in that they can be used as a brake to reduce diving speeds or landing runs by extending both flaps simultaneously.

The manoeuvrability of jet-powered flying-boats poses a few additional problems, *e.g.* if the engines are located close inboard, as is the tendency with British

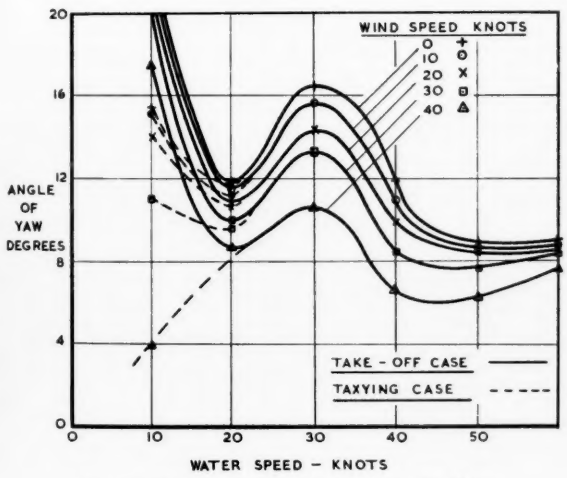

FIGURE 19. Boundaries of directional stability.

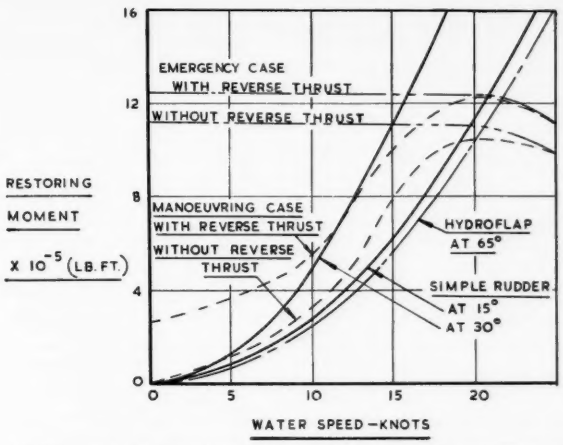

FIGURE 18. Comparison of restoring moments supplied by asymmetric thrust, simple water rudder and hydroflaps.

high speed jet aircraft, the flying-boat will suffer the disadvantage of having rather small asymmetric thrust moments. Even with conventional engine locations the advantage of reverse thrust is at present non-existent, although with the increasing demand for better braking on high speed aircraft the reversible thrust jet engine will probably become available before long.

An alternative to the conventional location of the jet engines would be the mounting of small auxiliary units at the wing-tips, which could also be used to provide any additional thrust required for take-off in very severe weather conditions. By making these units rotatable the thrust required, and thus the size and weight of the units, would be appreciably reduced.

Finally, a word about course-keeping qualities. If a flying-boat, proceeding on course, experiences a lateral disturbance, *e.g.* wind gust, dipping a float, which causes it to become yawed, the basic directional instability causes the aircraft to increase its divergence from the desired course.

Figure 19 shows typical boundaries of directional stability for a range of wind speeds. These indicate the angles of yaw at which the maximum available control moment equals the total upsetting moments of wind and water. If, due to slow application of corrective action, slow engine response rates, or other cause, the aircraft, under given conditions, exceeds the appropriate limiting yaw angle then the pilot will be unable to correct the motion, except by adjusting his forward speed to a value such that he is within the boundaries. This course is not always possible and the aircraft usually turns into wind.

Increasing the forebody length/beam ratio tends to increase the inherent directional instability of flying-boats, but this tendency can be offset by warping the forebody and by employing a long afterbody.

It is hoped that this brief outline of the developments in flying-boat design has shown that the application of a long narrow planing-bottom to a flying-boat hull not only results in an all-round improvement to its performance, but is essential if the craft is intended to operate throughout the year from moderately open sea localities or from ocean bases.

New Zealand Division

Sixth Annual Report: For Year Ended 31st December 1954

THE DIVISION is again able to report interesting progress both in regard to activities generally and to membership. It is encouraging to find that the major increase is from the younger men, notably from students in the Dominion.

The establishment of an organisation incorporated in New Zealand which would enable the Division to accept responsibilities in the custody of trust moneys and where necessary, liabilities, in sponsoring drives for funds, etc., has been approved in principle within the last few days and we have now been able to instruct our Solicitor to proceed with registration. There has been a need for this as, unlike the situation in the United Kingdom, the Royal Aeronautical Society is not a legal entity in this country.

The legal situation proved somewhat complicated and a good deal of effort was involved in arriving at the best solution. In this regard the Division was particularly fortunate in obtaining the appointment of Mr. Wylie, who was prepared to act as Honorary Solicitor and to give much of his valuable time and assistance.

Dr. A. M. Ballantyne, T.D., B.Sc., Ph.D., A.F.I.A.S., A.F.R.Ae.S., visited the Dominion in August and was able to see the conditions under which the Divisional Council and the Branches work. He addressed each of the Branches and met a large number of members. Introductions were arranged for him to many representatives of the aircraft operators, major airlines, repair organisations and aero clubs. The Divisional Council was very pleased to welcome him and later during a full meeting to have personal discussion on a number of major matters arising from the proposals to institute a Trust organisation which had not been found possible to deal with satisfactorily by correspondence. Dr. Ballantyne was also particularly helpful in placing the Society's case for recognition of its professional engineers before the Chairman of the Engineers Registration Board.

The New Zealand Divisional Banner arrived in September and is available for flying at the Society's pageants and other appropriate functions. The first stage of the project involving circulation of aeronautical films to Secondary schools has been completed. Results indicate that the scheme was successful.

No entries were received this year for the Design Study Competition for which the Division had offered several prizes.

Branches have found it difficult to obtain suitable Lecturers and a range of subjects to maintain maximum interest of their members. They are interested in the project explained by Dr. Ballantyne for tape-recording of Lectures made to the parent body and Branches in the U.K., to be made available to them. The Divisional Council is deeply appreciative of the work of the Branches and is aware that without this the activity of the Division would be quite barren.

During the year the Society's funds were transferred from the General Account to the Post Office Savings Bank. This will enable additional small earnings by way of Interest.

Mr. Pees of Palmerston North donated early volumes of *Flight* from 1909 and *Aeronautics* from 1907 which the Council were pleased to accept.

For assistance, encouragement and support throughout this, and preceding years, the Division records its sincere appreciation to the organisations of Tasman Empire Airways, Ltd., National Airways Corporation, the Civil Aviation Administration, the Shell and Vacuum Oil Companies, and the Royal New Zealand Air Force.

The Divisional Council for 1954 was elected by postal ballot and from these the following officers were elected:—

President	Mr. C. W. Labette
Vice-President	Mr. D. A. Patterson
Hon. Secretary	Mr. T. T. N. Coleridge
Hon. Treasurer and Assistant Secretary	Mr. A. O. Kemp

Council Members:—

Sir Arthur Nevill Mr. C. G. Andrews Air Cdre. G. Carter Mr. B. Cornthwaite Mr. E. A. Gibson Wing Cdr. W. G. Woodward	Wellington
Mr. H. F. T. Adams	Christchurch
Mr. A. W. Dingle	Palmerston North
Mr. G. N. Roberts	Auckland

Branch activities

AUCKLAND

In addition to ten other meetings the Branch held a public film evening, and an Aviation Interests Cocktail Party with Dr. A. M. Ballantyne, T.D., B.Sc., Ph.D., A.F.I.A.S., A.F.R.Ae.S., as the chief guest.

The Branch membership has increased from 141 to 161 even with 14 resignations due to transfer of members from Auckland.

The Branch has in progress a Walsh Brothers' Memorial essay competition.

PALMERSTON NORTH

The Branch activities included eleven meetings and one visit.

The Branch membership has fallen from 130 to 95, the main cause of this change being transfers away from the district.

WELLINGTON

In addition to six ordinary meetings the Branch held a social evening and also a public film evening. The

Branch membership has increased during the year from 159 to 169.

CHRISTCHURCH

Seven Branch meetings were held during the year including the one when Dr. Ballantyne spoke and at which representatives of other Societies and Institutes were invited to welcome him.

The Branch membership has risen from 31 to 75. A proportion of this big increase has, of course, been at the expense of transfers from some of the other Branches.

Membership of the Division

	As at January 1954	As at January 1955
Fellows	—	—
Associate Fellows	27	28
Associates	64	64
Graduates	7	7
Students	1	6
Companions	3	4
	102	109

Meetings

Papers and talks presented at meetings during the year were as listed below. Some of these have been given at more than one branch.

Murphy Distance Measuring Equipment by W. Parr.

High Speed Flight Testing by D. C. Stevenson.

Strain Gauges by F. Roper.

Fuel Additives by T. T. N. Coleridge.

Rotary Wing Aircraft and their Possibilities in New Zealand by Sir Arthur Nevill.

Modern Wing Plan Forms by Flight Lieutenant A. R. Chapman.

Impressions of a Recent Visit to the United Kingdom and America by Mr. A. J. Smaill.

The Society's Activities and Personalities, address by Dr. A. M. Ballantyne.

Impressions of a Recent Visit to Australia, and the Douglas DC-6 Aircraft by Mr. A. W. Dingle.

Demonstration and lectures by the Local Branch of the Model Aero Club.

DC-3 Replacements by Air Vice-Marshal Sir Leonard Isitt.

Team Work and Co-ordination in the R.N.Z.A.F. entry in the International Air Race by Wing Cmdr. R. F. Watson.

Trends in Aero Engine Design and the Research Background to the Development of Aviation Lubricating Oils by Mr. E. L. Bass.

Exploring the Air with Little Aircraft by Captain F. D. Bethwaite.

Helicopter Operation and Flight Performance by Mr. T. R. Pike.

Aspects of Modern Training of Military Pilots by Group Captain F. J. Rump.

Sailplane Activities in New Zealand by Mr. S. H. Georgeson.

Discussion—Heat Treatment of Steel.

Discussion—Method of Bonding Metals, by members of the Institute of Production Engineers.

In addition a large number of technical and semi-technical films have been shown at all Branches.

Divisional Council 1955.

The following are the officers and Council for 1955:

President—Air Commodore G. Carter, *Associate Fellow.*
Vice-President—D. A. Patterson, *Associate.*
Hon. Secretary—T. T. N. Coleridge, *Associate Fellow.*
Assistant Secretary and Treasurer—A. O. Kemp.
Hon. Auditor—B. W. Hoult.
Hon. Solicitor—G. A. Wylie.

Council Members: C. G. Andrews (Wellington) (*Associate Fellow*); B. Cornthwaite (Wellington) (*Associate*); E. A. Gibson (Wellington) (*Associate Fellow*); C. W. Labette (Wellington) (*Associate Fellow*); Sir Arthur Nevill (Wellington) (*Associate Fellow*); Group Capt. C. A. Turner (Wellington) (*Associate Fellow*); Wing Commander Woodward (Wellington) (*Associate Fellow*); A. J. Smaill (Christchurch) (*Associate*); M. R. Roper (Palmerston North) (*Associate Fellow*).

STATEMENT OF RECEIPTS AND PAYMENTS FOR THE YEAR ENDED 31st DECEMBER 1954

Receipts

	£	s.	d.
Funds on hand 1/1/54:			
National Bank of New Zealand	594	4	3
Petty Cash	1	0	1
Subscriptions, entrance and transfer fees received during year	262	17	0
New Zealand Broadcasting Service—broadcast fees	8	14	9
	£866	16	1

Payments

	£	s.	d.
Remittance to Royal Aeronautical Society, London, on account of 1953 Subscriptions	183	4	3
Branch Subscriptions for Division Members—Auckland Branch		10	6
Grant to Auckland Branch for film evening expenses	7	10	0
Expenses connected with visit of Royal Aeronautical Society Secretary, Dr. A. M. Ballantyne	20	19	0
Postage	10	10	3
Cable Charges	3	18	0
Stationery		8	0
General Expenses	4	0	6
Funds on hand 31/12/54:			
Petty Cash		9	1
National Bank of New Zealand	435	6	6
Post Office Savings Bank	200	0	0
	£866	16	1

I have audited the accounts of the Royal Aeronautical Society, New Zealand Division, and the above is a true and correct statement of receipts and payments for the year ended 31st December 1954.

F. H. TURLEY, A.R.A.N.Z., *Auditor.*
O. A. KEMP, A.R.A.N.Z., A.C.A.I., *Treasurer.*

TECHNICAL NOTES

Contributions to this Section of the JOURNAL *will be eligible for Journal Premium Awards and will normally be published within two months of being received.*

Deflection of Clamped Plates by Two-Step Membrane Analogue

by

V. CADAMBE AND R. K. KAUL

(National Physical Laboratory of India, New Delhi)

THE CLASSICAL Kirchhoff-Love Theory for the deflection of thin plates leads to fourth order Lagrange's differential equation, $D\nabla^4 w - q = 0$ for which a general solution is not always possible. Exact solutions are known so far only for a few special cases and, therefore, numerical solutions have often been tried. The advantage of numerical solution is that it can be applied easily to any plate plan form which is in marked contrast to the analytical method where, for mathematical reasons, definite restrictions have to be imposed on the geometrical shape of the plate. Among the various numerical methods, relaxation is the easiest, but when applied to solving a biharmonic equation, the process becomes extremely difficult and laborious as convergence is very slow and the unit relaxation operator cumbersome to deal with.

The notation used is:

M_x, M_y	bending moments per unit width along the edges $x=0$, a and $y=0$, a, respectively
$M=(M_x+M_y)/(1+\nu)$	
h	mesh size used in relaxation procedure
q	normal load per unit area
w	transverse deflection of plate (in.)
ν	Poisson's ratio, taken as 0·3
t	thickness of plate (in.)
D	flexural rigidity of plate (lb. in.) $=Et^3/12(1-\nu^2)$
E	modulus of elasticity, lb./in.^{2}
n, s	normal and tangential co-ordinates
x, y	rectangular co-ordinates
A_{mn}	coefficient used in series representation of deflection
Π	elastic strain energy of bending of plate (in. lb.)
m, n / p, q	positive integers

It was shown by Marcus that it is advantageous to replace Lagrange's equation of fourth order by two equations of the second order which represent the deflections of a membrane. The two equations are:

$$\frac{\partial^2 M}{\partial x^2} + \frac{\partial^2 M}{\partial y^2} + q = 0$$

$$\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{M}{D} = 0$$

Received February 1955.

For simply-supported plates of polygonal shape with rectilinear boundaries, the edge conditions are:

$$w = 0$$

$$M_n = \frac{\partial^2 w}{\partial n^2} + \nu \frac{\partial^2 w}{\partial s^2} = 0$$

Since $w=0$, at the straight boundary $\partial^2 w/\partial s^2 = 0$ and observing $M_n = 0$ at the simply-supported edge, we conclude that $\partial^2 w/\partial n^2 = 0$ and therefore $M=0$. The simply-supported plate problem thus reduces to the solution of the two equations

$$\nabla^2 M + q = 0 \quad \text{with } M = 0 \text{ on the boundary}$$

$$\nabla^2 w + \frac{M}{D} = 0 \quad \text{with } w = 0 \text{ on the boundary.}$$

This system of simultaneous differential equations can be easily solved by the relaxation procedure[1] as the boundary values are specified and entail no difficulty. For clamped edges, the boundary conditions are $w=0$ and $\partial w/\partial n = 0$. Again for rectilinear clamped edge $\partial^2 w/\partial s^2 = 0$ along the boundary, and it can be shown that $\partial^2 w/\partial n^2 = -M/D$. From the relaxational point of view, the two equations with appropriate boundary conditions to be solved in succession are

$$\nabla^2 M + q = 0 \quad \text{with } M = -D\frac{\partial^2 w}{\partial n^2} \text{ on the boundary}$$

$$\nabla^2 w + \frac{M}{D} = 0 \quad \text{with } w = 0 \text{ on the boundary}$$

which when represented in *centre-finite difference* form are:

$$\sum_{i=1}^{4} M_i - 4M_0 + qh^2 = 0 \text{ with } M = -2wD/h^2 \text{ on the boundary}$$

$$\sum_{i=1}^{4} w_i - 4w_0 + \frac{M_0}{D}h^2 = 0 \quad \text{with } w = 0 \text{ on the boundary.}$$

It is, therefore, necessary to take two similar nets, one for w and the other for M as shown in Fig. 1, and start with the net w by assigning *membrane* values to all nodes in the net with $w=0$ on the boundary. The boundary values for the net M are calculated from the nodal values of the *bordering nodes* of net w according to the relation $M = -2wD/h^2$. Values are assigned at other remaining points in this net and the residuals relaxed according to Poisson's relaxation pattern. Having got probable values of M at all points in the net, the

residual at each node in the net w can now be correctly determined, since M enters in the residual formula for w. The liquidation of these residuals is carried out according to Laplace's relaxation pattern, for while relaxing this net no account is taken of M. The other net is next considered and new values are assigned to the boundary on the basis of the change in the value of w on the *bordering nodes* of net w. This constitutes one complete cycle and such cycles of operations are repeated till the residuals left over are negligibly small.

To illustrate the process, a square clamped plate is taken as an example, as theoretical solution for deflection is known and the accuracy obtainable by relaxation can be compared. The process is worked out only for one-eighth of the plate plan form, for reasons of symmetry. The size of the plate is $(4l \times 4l)$ and the final mesh size $h=l/2$. It should be observed that the boundary value of M on the second net is $-8w$, since reciprocal of h^2 enters in the relation governing M on the boundary of the second net.

Before advancing to a mesh size of $h=l/2$ relaxation is carried out on coarser mesh lengths. The maximum deflection w_0 obtained with mesh length of $h=2l$ is $0{\cdot}6666\, ql^4/D$ and for mesh length $h=l$, $0{\cdot}4606\, ql^4/D$. Having the value of w_0 for three different mesh lengths, $h=2l$, l and $l/2$, a better approximation can be obtained by extrapolation. The *error* e can easily be corrected if we assume that

$$e=\bar{w}_0-w_0=h^2\phi_1(x,y)+h^4\phi_2(x,y)+\ldots.$$

where $\phi_1(x,y)$ and $\phi_2(x,y)$ are not only independent of mesh size h but also constants for the particular node in this case and $\bar{w}_0$ is the correct value of w_0 at the centre of the square plate. The three values of w_0 for three different mesh lengths h yield a system of three simultaneous equations with three unknowns, $\bar{w}_0$, ϕ_1 and ϕ_2 (terms containing h^6 and higher powers of h are neglected). The extrapolated value of $\bar{w}_0$ is $0{\cdot}33857\ ql^4/D$ and for a plate size of $(a\times a)$ where $a=4l$,

$$\bar{w}_0=0{\cdot}01442\, qa^4/(Et^3)$$

To gain an idea of the accuracy achieved with such a coarse net, the value obtained by relaxation is compared with that obtained by Timoshenko[2] and also by Evans by analytical methods. The result based on energy method where only one parameter A_{11} is considered, is also worked out in order to assess the degree of approximation.

The series for deflection w is taken in the form

$$w=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}A_{mn}\left(1-\cos\frac{2\pi mx}{a}\right)\left(1-\cos\frac{2\pi ny}{a}\right)$$

and the energy integral Π to be minimised is

$$\Pi=\tfrac{1}{2}\int_0^a\int_0^a[D(\nabla^2 w)^2-2qw]\,dx\,dy$$

The minimising condition $\partial\Pi/\partial A_{mn}=0$ gives

$$4D\pi^4\{[3m^4+3n^4+2m^2n^2]A_{mn}+\sum_{p=1\text{ except }p=n}^{\infty}2m^4A_{mp}+\sum_{q=1\text{ except }q=m}^{\infty}2n^4A_{qn}\}-qa^4=0$$

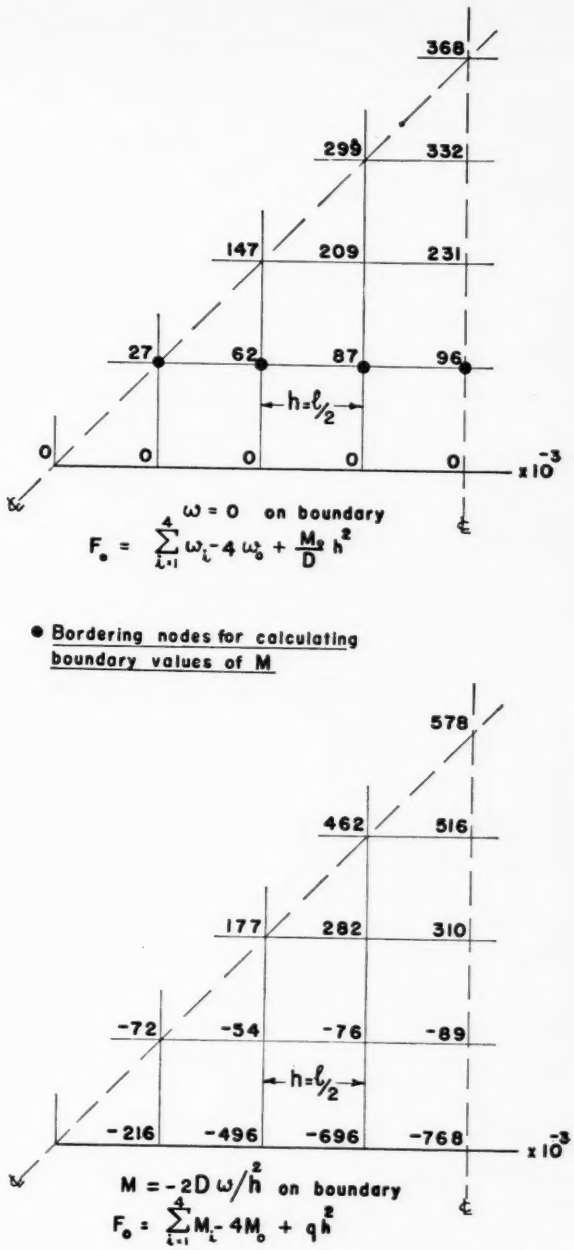

FIGURE 1. Relaxation network for the two-variable technique.

For $m=n=1$, $A_{11}=qa^4/32\pi^4D$, and therefore at $x=y=a/2$,

$$\bar{w}_0=qa^4/8\pi^4D=0{\cdot}01400\, qa^4/(Et^3).$$

The value obtained by Timoshenko and by Evans is $0{\cdot}0138\, qa^4/(Et^3)$. The error is 3·0 per cent. when compared with the Rayleigh-Ritz solution and 4·5 per cent. compared with that of Timoshenko. A much greater accuracy can be achieved if the mesh size is made finer, but for the purpose of illustrating the method, greater accuracy was not aimed at. For the same reason plates

with curved boundaries were not considered as they would not introduce any new problem from the relaxation point of view.

It may be interesting to note that problems having mixed boundary conditions (partly clamped and partly supported) can similarly be tackled by this two-step membrane analogue. Similarly, deflection of clamped plates of variable rigidity $D(x, y)$ can be determined. In such a case the two finite difference equations are

$$\sum_{i=1}^{4} M_i - 4M_0 + qh^2 = 0$$

$$\sum_{i=1}^{4} w_i - 4w_0 + \frac{M_0 h^2}{D_0(x, y)} = 0.$$

Since $D(x, y)$ is varying from point to point, its correct value at each node should be calculated, and while calculating the residuals of net w, corresponding values of $D_0(x, y)$ should be used at each node. The relaxation procedure, however, remains the same.

Knowing the deflection w at every point in the net, the bending moments M_x, M_y, shear forces Q_x, Q_y and the twisting moment T_{xy}, can also be determined if the differential expressions representing these are first put in *centre-finite difference* form.

ACKNOWLEDGMENT

The assistance of S. Viswanathan in the preparation of this note is gratefully acknowledged.

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Power Loss and Fuel Pressure Rise due to Centrifugal Pumping in Tip-Driven Helicopter Rotors

by

P. R. PAYNE

WHEN tip-mounted engines are employed on a helicopter rotor, such as lightweight turbines, ram-jets or pulse-jets, the action of the fuel flowing along the blade gives rise to a power loss. For a ram-jet helicopter this is of the order of 6 per cent. of the total power requirement of the rotor system. In addition, if the fuel injection nozzles in the combustion chamber face upstream this leads to an additional power loss of 1-6 per cent. of the total power, and it is evident that these effects should be allowed for in helicopter performance calculations. It is shown for a ram-jet helicopter that the total spraying and centrifugal pumping loss is of the same order as the total transmission and tail-rotor power loss for a conventional shaft-driven helicopter. The same effect can be demonstrated for pressure-jet rotors, where it has an even greater magnitude.

Expressing the power loss due to spraying and centrifugal pumping as a loss of engine thrust it is shown that it depends upon rate of fuel flow and tip speed only, and it is therefore suggested that the effect should always be allowed for in curves of engine net thrust, rather than in helicopter rotor power loss calculations.

Finally, an equation is developed for fuel pressure at the tip of a rotor, and it is shown that this pressure increases with the rate of fuel flow. This increase is largely offset by wall friction in the fuel supply pipe and it is concluded that, for practical purposes, the fuel pressure at the tip is equal to half its mass density times the square of the tip speed ($P = \frac{1}{2}\rho V_T^2$).

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NOTATION

a	total orifice area of spray gear
A	cross-sectional area of stream tube
C_D	discharge coefficient
g	acceleration due to gravity
P	pressure in fuel line
q	volumetric fuel flow
Q	torque about hub centre
r	radial distance from hub centre
R	radius of tip-mounted engine
(S.F.C.)	specific fuel consumption
T	net thrust of tip-mounted engine
ΔT	loss of net thrust
V_T	circumferential velocity of tip
V_{rad}	radial velocity of fuel in blade
ρ	density of fuel
ω	rotational speed of rotor

THEORY

Centrifugal Pumping Loss

Consider an element of fuel in a pipe at radius r from the hub centre. If the stream tube has area A, the mass of the fuel element will be $\rho A dr$ and the corriolus force acting upon it will be $2\rho A dr \omega V_{rad}$. Thus the torque exerted by this elemental force about the hub centre is

$$dQ = 2\rho A \omega V_{rad} r\, dr$$

and the total torque

$$Q = 2\rho A \omega V_{rad} \int_0^R r\, dr = \rho A V_{rad} \omega R^2. \quad . \quad (1)$$

Expressing this as a loss of thrust ΔT at the tip-mounted engine

$$\Delta T = \frac{Q}{R} = \rho A V_{\text{rad}} V_T = \rho V_T q \quad . \quad (2)$$

where q is the fuel flow in ft.^{3}/sec. This result is physically easy to understand, since ΔT is the force expended in accelerating the fuel mass ρq to a velocity V_T.

Equation (2) can be put into a more descriptive form by writing

$$\rho q = \frac{(\text{S.F.C.})\,T}{3{,}600\,g}$$

so that

$$\frac{\Delta T}{T} = \frac{(\text{S.F.C.})\,V_T}{3{,}600\,g} \quad . \quad . \quad . \quad (3)$$

As Fig. 1 shows, the product (S.F.C.) V_T (taken from the curves in Ref. 1) is substantially constant in the design case, a typical value being about 7,000. Thus for project design purposes a sufficiently good approximation for centrifugal pumping is

$$\frac{\Delta T}{T} = \frac{7{,}000}{3{,}600\,g} \simeq 6{\cdot}0 \text{ per cent.} \quad . \quad (4)$$

Forward Facing Spray Loss

The force on the spray gear will be the mass flow ρq times the initial spray velocity q/aC_D where a is the total orifice area open. The loss of thrust is therefore

$$\Delta T = \frac{\rho q^2}{aC_D} \quad . \quad . \quad . \quad . \quad (5)$$

In a design where the orifice area is fixed ΔT will vary as the square of the fuel flow, but where fuel flow is varied by opening or closing orifices it will vary linearly.

Using the same substitution as before to obtain an order of magnitude

$$\Delta T = \left(\frac{(\text{S.F.C.})\,T}{3{,}600\,g}\right)^2 \Big/ \rho a C_D$$

$$\frac{\Delta T}{T} = \left(\frac{(\text{S.F.C.})}{3{,}600\,g}\right)^2 \frac{T}{\rho a C_D} \quad . \quad . \quad (6)$$

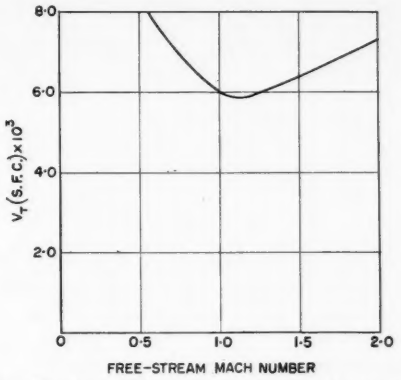

FIGURE 1. Variation of the product V_T (S.F.C.) for helicopter ram-jets (design case variation).

Since T/aC_D is roughly constant for a given design of spray gear an approximate figure can again be obtained for percentage power loss. A typical ram-jet would give the highest loss, and taking $T = 80$ lb., (S.F.C.) = 8·0 lb./lb./hr., $\rho = 1{\cdot}4$ slugs/ft.^{3}, $aC_D = 0{\cdot}22 \times 10^{-4}$ ft.^{2}:

$$\frac{\Delta T}{T} = 1{\cdot}24 \text{ per cent.} \quad . \quad . \quad (7)$$

Thus the total loss due to pumping and upstream spraying is over 7 per cent., a value which is of the same order as the total transmission and tail-rotor power losses in a conventional shaft-driven helicopter.

Note that when there are no important losses and the fuel pressure $P = \frac{1}{2}\rho V_T^2$ (*see* below) the initial spray velocity is V_T. Then

$$\Delta T = \rho q V_T \quad . \quad . \quad . \quad (5a)$$

The total loss is then twice the pumping loss for an upstream injection (12 per cent.) or zero for downstream injection. This considerable loss from upstream injection must be balanced against the higher combustion efficiency obtained, and the lower air temperature after compression in the diffuser.

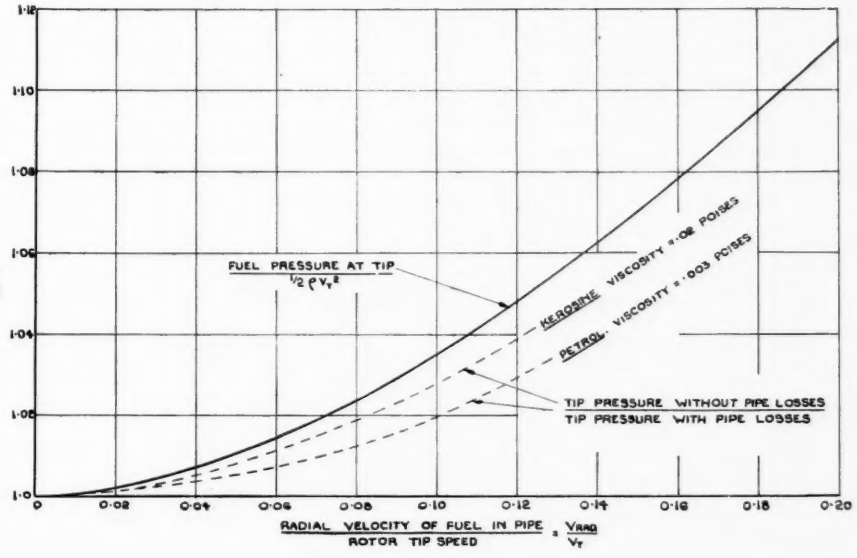

FIGURE 2. Variation of fuel pressure with fuel flow at tip-mounted engine.

Fuel Pressure Rise due to Centrifugal Force Field

Considering an element of fuel moving along the blade at a velocity V_{rad} while the blade rotates at an angular velocity ω, it can be shown that the resultant velocity of the element is $\omega(r^2+V_{rad}^2/\omega^2)^{\frac{1}{2}}$ and that the local radius of curvature is $(r^2+V_{rad}^2/\omega^2)^{\frac{1}{2}}$. Thus the centripetal acceleration on the element is

$$\omega^2\left(r^2+\frac{V_{rad}^2}{\omega^2}\right)^{\frac{1}{2}}$$

acting at an angle $\phi=\tan^{-1}V_{rad}/(\omega r)$ to the blade centre line. Since ϕ is small, $\cos\phi\simeq 1{\cdot}0$ and the centripetal force acting on an element Adr is

$$dF=\rho A dr\omega^2\left(r^2+\frac{V_{rad}^2}{\omega^2}\right)^{\frac{1}{2}}.$$

The pressure at any radius r is therefore

$$P=\rho\omega^2\int_0^{r_1}\left(r^2+\frac{V_{rad}^2}{\omega^2}\right)^{\frac{1}{2}}dr$$

$$=\tfrac{1}{2}\rho\omega r_1\left[(\omega r_1)^2+V_{rad}^2\right]^{\frac{1}{2}}+\tfrac{1}{2}\rho V_{rad}^2\sinh^{-1}\frac{\omega r_1}{V_{rad}} \quad (8)$$

$$P=\tfrac{1}{2}\rho V_T^2\left[\left(1+\frac{V_{rad}^2}{V_T^2}\right)^{\frac{1}{2}}+\frac{V_{rad}^2}{V_T^2}\sinh^{-1}\frac{V_T}{V_{rad}}\right]. \quad (9)$$

Note that when $V_{rad}=0$

$$P=\tfrac{1}{2}\rho V_T^2. \quad . \quad . \quad . \quad (9a)$$

Since $V_{rad}=q/$(pipe cross-sectional area) it is evident that a large bore fuel pipe minimises the rise in pressure due to radial flow. A small bore pipe, although giving a higher centrifugal pressure, also has a higher pressure loss due to wall friction. This effect can be calculated in the normal way, using any standard work of reference.

In Fig. 2 equation 9 is plotted against radial velocity, and for comparison typical pipe losses are included for a small ram-jet rotor. It is evident that for design purposes the small rise in pressure due to radial flow is largely offset by pipe losses and that the fuel pressure at the tip can therefore be calculated from equation (9*a*). At $V_T=800$ ft./sec., the ram-jet helicopter example in Fig. 2 would have a tip pressure of 3,110 lb./in.^{2} using petrol as fuel, and a typical supersonic rotor would have fuel pressures of the order of 15,000 lb./in.^{2} to contend with, unless restrictive orifices were placed in the blade.

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Empirical Formulae for the Determination of Stress Curves

by

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THE PAPER by A. C. Nicholls in the October 1954 JOURNAL (p. 724) describes two empirical equations neither of which possesses the first essential of an acceptable strain hardening function, namely that the stress attained in a preliminary straining operation shall become explicitly the threshold stress at which subsequent deformation begins. Eight years of study and the analysis of hundreds of published curves have convinced me that the exponential function put forward in 1948[1] faithfully reflects the strain hardening process. Far from being empirical, it can readily be deduced from a few simple and credible assumptions, and has counterparts in many branches of physics[2].

The basic equation connecting the true stress, S, with the logarithmic strain, η, is

$$\frac{dS}{d\eta}=\frac{S_\infty-S}{\eta_c} \quad . \quad . \quad . \quad (1)$$

which on integration can be written in the alternative forms

$$\frac{S-S_0}{S_\infty-S_0}=1-\exp\left(-\frac{\eta}{\eta_c}\right) \quad . \quad . \quad . \quad (2)$$

$$S=S_\infty-\left(S_\infty-S_0\right).\exp\left(-\frac{\eta}{\eta_c}\right). \quad (3)$$

$$\eta=\eta_c\,.\,1n\,\frac{S_\infty-S_0}{S_\infty-S}. \quad . \quad . \quad . \quad (4)$$

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where S_0 is the *threshold stress* at which plastic deformation begins, S_∞ is the *asymptotic stress* attained after severe deformation, and η_c is the *characteristic strain* which determines the shape of the curve.

If S_1 is the stress attained after the application of a particular strain η_1, then

$$\eta-\eta_1=\eta_c\left(1n\frac{S_\infty-S_0}{S_\infty-S}-1n\frac{S_\infty-S_0}{S_\infty-S_1}\right)=\eta_c\,.\,1n\frac{S_\infty-S_1}{S_\infty-S}. \quad . \quad . \quad . \quad (5)$$

This is identical with the original equation except for the substitution of S_1 for the original threshold stress S_0 and subtraction of the corresponding strain η_1. Thus the function fulfils the essential requirement that the stress attained in a preliminary operation becomes explicitly the stress at which deformation in excess of the applied strain begins.

The author rightly emphasises the desirability of easy differentiation and integration. Equation (1) shows that the slope of the stress-strain curve is linear with respect to stress, while the work done per unit volume, W, is simply

$$W=\int_0^\eta S\,.\,d\eta=S_\infty\eta-(S-S_0)\,\eta_c. \quad . \quad (6)$$

Important physical inferences, beyond the scope of this note, can be deduced from these derived functions.

There can be little doubt that elastic and plastic deformations are distinct processes, and this is reflected

in the fact that the initial slope of the strain hardening curve for ductile metals is much less than Young's modulus. The elastic line is invariably linked to the strain hardening curve by a short fillet which belongs properly to neither. The fillet doubtless represents the gradual spread of the plasticising process through the metal, and its shape depends on the local distribution of stress in relation to the orientation, size and nature of the individual crystals. It is hardly to be expected, therefore, that it should conform to any particular mathematical function, and it is pleasantly surprising to find that it can generally be represented by a very short preliminary régime having the same form as the main strain hardening equation, but with smaller constants. The fillet gives tangential junction with the elastic line on the one hand, and with the strain hardening curve proper on the other.

An approximation to the equation of the fillet can be deduced in the following manner. At any typical sectional area, A, let the proportion which has become plasticised at the instant under consideration be x. Then the plasticised area is xA while that still carrying elastic stress is $(1-x)A$. If the stress supported by the elastic parts is S_e and that supported by the plastic parts is S_p, then the total load, P, required to produce deformation is

$$P=(1-x)AS_e+xAS_p. \quad . \quad . \quad (7)$$

Dividing across by A and solving for x,

$$x=\frac{S-S_e}{S_p-S_e} \quad . \quad . \quad . \quad . \quad (8)$$

where S is the observed stress on the section. When the applied stress first reaches the neighbourhood of the elastic limit, the likelihood that any small increment of strain will cause part of the area to become plasticised is high, for there are countless local positions where it could do so. When, however, only a small part of the area remains elastic, the strain will be likely preferentially to affect the already plasticised regions, leaving the elastic parts as small islands. That is to say, the chance that any small increment of strain will increase the plasticised area is roughly proportional to the area remaining to be plasticised, so that

$$\frac{dx}{d\eta}=\frac{1-x}{\eta_e'} \quad . \quad . \quad . \quad (9)$$

where η_e' is a constant of proportionality in logarithmic strain units. Integrating,

$$-\ln(1-x)=\frac{\eta}{\eta_e'}+C. \quad . \quad . \quad (10)$$

Now x is zero when the strain is that observed at the limit of proportionality, say η_e, so that the integration constant is $-\eta_e/\eta_e'$, and

$$x=1-\exp\left(-\frac{\eta-\eta_e}{\eta_e'}\right). \quad . \quad (11)$$

Combining equations (8) and (11), and rearranging,

$$\eta-\eta_e=\eta_e'\ln\frac{S_p-S_e}{S_p-S}. \quad . \quad (12)$$

Except for the substitution of S_p for S_∞, this is the counterpart of equation (5). Strictly S_p is not constant, but it changes very little for the small strains with which the fillet is concerned, and can be replaced by a suitably selected constant value, S_∞', without appreciable error. This is a compromise value slightly above the threshold stress of the main strain hardening function, to allow for the small degree of strain hardening attributed to the strains in the fillet.

The constants of the fillet must be adjusted to make tangential contact with the elastic line at the limit of proportionality. This condition is expressed by

$$\left(\frac{dS}{d\eta}\right)_{S=S_e}=\frac{S_\infty'-S_e}{\eta_e'}=E \quad . \quad . \quad (13)$$

where E is Young's modulus. At the upper end of the fillet, tangential junction with the strain hardening curve occurs at the transition stress, S_t, found by equating the slopes of the two branches. It can readily be shown that

$$S_t=\frac{\eta_e S_\infty'-\eta_e' S_\infty}{\eta_e-\eta_e'}. \quad . \quad . \quad (14)$$

The transition stress is subject to the requirement that the corresponding strain, η_t, shall be the same for both sets of constants, so that

$$\eta_t=\eta_e\ln\frac{S_\infty-S_e}{S_\infty-S_t}=\eta_e'\ln\frac{S_\infty'-S_e}{S_\infty'-S_t}+\eta_e. \quad . \quad (15)$$

The information presented in Fig. 1 of the paper under discussion is confined to the elastic extension and fillet only. Presumably it records nominal stresses and fractional extensions, not true stresses and logarithmic strains to which the exponential equation applies. For small strains, however, the error is not great, and the constants for the fillet as plotted are:

Threshold stress (limit of proportionality)	49×10^3 lb./in.^{2}
Asymptotic stress	74×10^3 lb./in.^{2}
Characteristic strain	$2{\cdot}36\times10^{-3}$
Elastic strain at threshold stress	$4{\cdot}62\times10^{-3}$

These constants give the following values for plotting:

Stress lb./in.^{2}	*Calculated strain*	*Calculated plus elastic strain*
50×10^3	$0{\cdot}09\times10^{-3}$	$4{\cdot}71\times10^{-3}$
55	0·65	5·27
60	1·37	5·99
65	2·41	7·03
70	4·33	8·95
72	5·96	9·58
72·5	6·64	11·26

The points so computed lie upon the curve in the diagram within the limits to which the latter can be read, while the slope at the threshold stress, from equation (13), is exactly equal to the stated value of Young's modulus, namely $10{\cdot}6\times10^6$ lb./in.^{2}. The shape of the curve strongly suggests that the stated value of the limit of proportionality, $49{\cdot}7\times10^3$ lb./in.^{2}, is slightly too high, and it certainly appears to be so from the drawing of the diagram.

In addition to its theoretical advantages, the exponential function is exceedingly easy and quick to handle; the foregoing analysis of Fig. 1 was completed

in less than ten minutes. Equation (1) provides a powerful means of locating trial values for the constants. With the help of a transparent protractor pivoting about a pin and a table of natural tangents, the curve is roughly differentiated at a series of stresses, and the best straight line through the points so obtained reveals the asymptotic stress by its intercept on the ordinate, and, after allowing for the scales of plotting, the characteristic strain by its slope. Alternatively, if η_1, η_2 and η_3 are any three strains in arithmetic progression, all belonging to the same régime, while S_1, S_2 and S_3 are the corresponding stresses, then

$$S_\searrow = \frac{S_2^2 - S_1 . S_3}{2S_2 - (S_1 + S_3)} \quad . \quad . \quad . \quad (16)$$

$$\eta_c = \frac{\eta_2 - \eta_1}{\ln \dfrac{S_\searrow - S_1}{S_\searrow - S_2}} . \quad . \quad . \quad . \quad (17)$$

$$S_0 = S_\searrow - (S_\searrow - S_1) . \exp \frac{\eta_1}{\eta_c} \quad . \quad . \quad (18)$$

The tentative constants found by either of these methods are tested and adjusted as necessary by setting up a series of stresses and computing the strains from equation (4), which is slightly more speedy to operate than equation (3). In dealing with successive régimes special care is necessary to ensure that the conditions imposed by equation (15) are met, as otherwise the two branches may remain separated by a gap.

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A. C. NICHOLLS

DR. VOCE is perfectly correct in stating that neither of the two empirical equations satisfies the essential requirement of no plastic deformation at the threshold stress. From a purely theoretical consideration, in fact, this stress should be zero. On closer analysis, however, it will be observed that over the relevant range the error involved in the stress-strain curve under consideration is not very serious. The greatly enlarged view of part of this curve (Fig. A) clearly indicates this point. Dr. Voce also suggests quite rightly that the value of the limit of proportionality $49{\cdot}7 \times 10^3$ lb./in.^{2} from Fig. 1 of the original paper (October JOURNAL 1954, p. 725) is too high. The fact is inevitable owing to the nature of the curves. He may possibly be right from test evidence, but as is well known, the *LP* is not the easiest of points to determine experimentally.

As a matter of interest the following plot of stress scatter against strain for some three dozen compression tests on Noral 75S shows the sort of dependability that can be placed on the *LP* (Fig. B). Had the test points been determined from design values rather than mean ones, the *LP* would have been relatively much less. That, incidentally, was the reason for not taking its value into determination of the curves. While not attempting to justify the fact that the curves fail to pass through this point, it is comforting to know that the errors are on the safe side.

As Dr. Voce correctly presumed, the nominal stresses and fractional extensions have been used

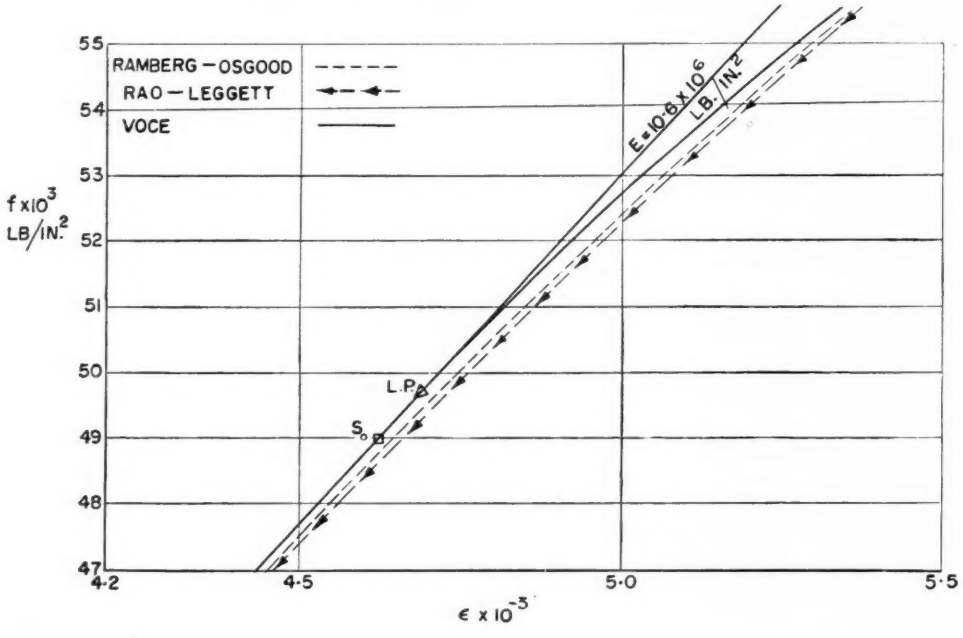

FIGURE A.

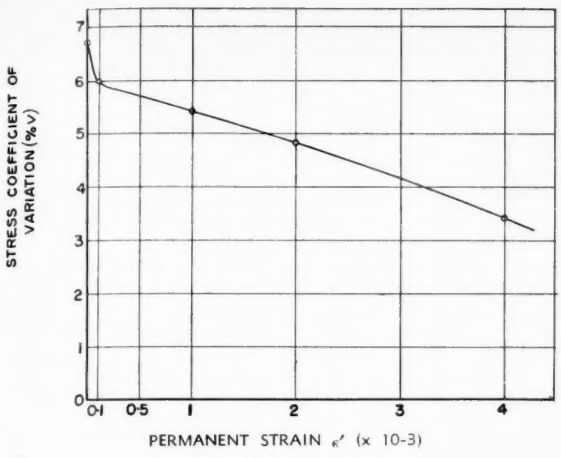

FIGURE B.

instead of the true stresses and logarithmic strains, but as the range that is of interest is well within the fillet region no appreciable errors are involved.

Unfortunately such a curve is not always available and, furthermore, the strains as presented in the aeronautical industry are nearly always proof strains. If, for instance, $f_{0\cdot5}$, f_1 and f_2 were given, the formula corresponding to equation (16) of Dr. Voce's comment would take the following form:

$$\frac{0\cdot001E+(f_2-f_1)}{0\cdot0005E+(f_1-f_{0\cdot5})}=\log\left[\frac{S_\infty-f_1}{S_\infty-f_2}\right]\div\log\left[\frac{S_\infty-f_{0\cdot5}}{S_\infty-f_1}\right].$$

Where tensile values were available, as for instance in AP 970, Vol. II, perhaps the asymptotic stress could be replaced by the true ultimate tensile one. The stress values could then be suitably adjusted so as to satisfy the above identity.

The exponential function propounded by Dr. Voce appears to be dependent on an existing stress-strain curve or alternatively on three strains in arithmetic progression.

Alternatively, where the limit of proportionality is known, perhaps Dr. Voce's second equation could be expressed in the following form:

$$S'=\bar{S}\left[1-\exp\left(-\frac{1}{\bar{S}}(\varepsilon'E+S')\right)\right]$$

where

$S'=S-S_0$

$\bar{S}=S_\infty-S_0$

$\varepsilon'=$ permanent strain.

In the example under discussion the value of 24,000 lb./in.^{2} for $\bar{S}$ can readily be obtained by trial and error. The equation then yields the following information:

ε' $\times 10^{-3}$	S' (calculated) $\times 10^3$ lb./in.^{2}	S' (test) $\times 10^3$ lb./in.^{2}
0		0
0·1	6·6	6·6
0·5	12·6	12·6
1·0	16·0	15·9
2·0	19·6	19·6
4·0	22·4	22·9

Thus, not only are the foregoing figures more accurate than those quoted by Dr. Voce, but both Young's modulus and the limit of proportionality remain at their original test values.

It would be very interesting to read the comments of other readers on this subject.

In conclusion, thanks are due to Dr. Voce for his frank comments and for drawing attention to his excellent paper of 1948—a paper which deserves to be much more widely known.

THE LIBRARY

Reviews

MACHINE DRAWING AND DESIGN. *W. Abbott. Blackie, London, 1954. 253 pp. Diagrams. 15s.*

This well-known book has now reached its sixth edition and has again been revised and brought up to date. Copies of the previous editions are to be found on the shelves of technical libraries throughout the country and the majority of engineers and students will already be familiar with the nature and presentation of the contents.

The book deals in the first part with the elements of machine drawing, the basic principles of projection, sectioning and dimensioning being adequately covered. The mechanical aid to perspective drawing using a drawing board with curved edges is intriguing and is something quite new to the reviewer.

Riveting is dealt with in a straightforward manner and the design of riveted joints is quite well done. The statement on page 48, Item 4, that failure due to fracture at margin cannot occur provided that the dimension is equal to or greater than the diameter of the bolt hole may be true, but individual cases should be checked for this condition and a formula for determining the minimum dimension might with advantage be included. The riveted joints described are all of the concentrically loaded variety and examples of excentrically loaded types might prove a useful addition.

Thread forms and terminology are covered quite adequately and various methods of representing screw threads on drawings are illustrated, as are examples of locknuts, setscrews, keys and so on.

The section devoted to cams is brief but sufficient to serve as an introduction to the subject. Examples are given of cam profile layout, and displacement, velocity and acceleration diagrams are also shown.

Bearings are illustrated with the familiar pedestal variety and the applications of ball and roller races are also covered. The inclusion of the Michell thrust bearing in this section is to be commended.

Dr. Abbott presents the subject of gearing in a most clear and lucid manner and a wealth of information is contained in some 16 pages. Spur, helical, bevel and worm gearing each receive their due share of attention and exercises showing the methods of drawing the various forms are very well illustrated.

Brief reference is made to factors influencing design and a few pages are devoted to limits, fits and tolerances.

Interspersed between the sections mentioned are numerous examples of mechanical engineering drawing which students will find extremely valuable as exercises and for reference purposes. Part II of this volume consists of exercises supplementary to Part I and questions from past examination papers.

The author, in the Preface, says ". . . it is intended to provide an intermediate course in Machine Drawing and Design for students of mechanical engineering who are following university and technical college courses or are preparing for the examinations of the professional engineering institutions. . . ." Dr. Abbott has carried out his intention remarkably well, the presentation of the subject matter is straightforward and the reproduction of the line drawings is very good indeed.

Aircraft component drawing is not covered in this book and it was not intended that any should be so included. This is a book dealing with the basic principles of machine drawing and design and as such can be thoroughly recommended to students who are training for the profession. —E. J. MANN.

GRAPHICS IN ENGINEERING AND SCIENCE. *A. S. Levens. John Wiley, New York. Chapman & Hall, London, 1954. 696 pp. Diagrams. 56s.*

This is not an easy book to review as it ranges far and wide over the whole field of graphics and there is so much contained in its nearly 700 pages that space alone must dictate the course which this review can take.

Professor Levens in his introduction stresses the importance of engineering students developing proficiency in the use of the three languages of communications—English, the language of symbols (mathematics, physics and chemistry), and graphics. It is with the latter that we are mainly concerned in this volume.

First of all, the book is divided into three parts:

(1) Fundamentals and Applications of Orthogonal Projection.

(2) Technical Drawing Practices.

(3) Graphical Solutions and Computation.

Part 1 consists of 8 sections; the first is devoted to the introduction in which the author outlines the scope of the work, and so well is it done that it might in itself serve as a comprehensive review.

Section two. Principles of Projection.—A straightforward elementary treatment of the subject leading to

Section three. Application of the Basic Principles of Orthogonal Projection.—A most useful section in which the author touches on the projection of solids before going on to the projection of lines and planes in space. True length of lines are obtained by the normal projection method as well as by rotation. Examples showing applications to windscreen and undercarriage problems are included in the text.

Section four. Developments.—Devoted to the development of such items as oblique cones, truncated cylinders and transition pieces of various types.

Section five. Visibility. — Consisting of five pages devoted to an explanation of the methods employed to determine the visibility of lines in a supplementary view from information given on two existing views.

Section six. Angle Problems.—This is another short section which describes methods employed to find the true angles between two intersecting lines, two non-intersecting lines and between a line and a plane. The procedure outlined is that normally used to solve problems of this nature.

Section seven. Intersections.—Devoted to problems of the intersection of lines and plane surfaces, lines and conical sufaces, lines and cylindrical surfaces. The methods employed are quite orthodox and call for no particular comment.

Section eight. Pictorial Drawing. — Details are given here of the principles of isometric drawing together with examples of oblique drawing. Reference is made to the isometric grid and an illustration shows its use. Examples are given showing methods for drawing oblique circles.

Part 2. Section nine. Sections and Conventions. — Straightforward treatment of the methods employed to

show, by sectioning, details of machined parts which are not capable of being shown in the orthodox views.

Section ten. Threads and Fasteners. — An extensive chapter covering bolts, nuts, washers, rivets, locking devices and keys. Information on coil springs is also included but the association of springs with the title of the section is somewhat obscure.

The terminology of screw threads and methods of drawing are virtually universal, but as one would expect in a book originating in America the proprietary brands of lock nuts are those of American manufacture and will not be familiar to the great majority of British readers. This is not a criticism, as a complete volume would be necessary to include the vast number of lock nuts appearing in the world markets.

It should be emphasised that this chapter is illustrative only; the design of bolted and riveted joints is not included.

Section eleven. Cams and Gears.—The first part deals with cams and followers of various types. The treatment is concise and clear and the text is supplemented with worked examples of cam profile design.

The second part, devoted to gears, covers the basic concepts of gear design and includes numerous worked examples. Spur, bevel, worm, and helical types of gearing are covered briefly but adequately.

Section twelve. Dimensioning Practices and Applications.—This section deals with recommended methods of dimensioning plate fittings, machined parts, drill holes, chamfers, etc. In most cases the dimensioning technique illustrated follows very closely on the British Standards Institution's report B.S. 308, 1953, but the limit system is that of the American Standards Association and is not directly applicable to drawings prepared in this country.

Part 3. Section thirteen. Graphical Solutions and Computations.—This is devoted to graphical mathematics and describes methods whereby addition, subtraction, division and multiplication can be carried out by the geometrical construction of curves and charts.

Section fourteen. Functional Scales.—This deals with the preparation of scales representing values of the variable in a given expression and having the distances to the graduations laid off in proportion to the corresponding values of the function of the variable.

Adjacent and non-adjacent scales for solving equations of the form $f_1(u)=f_2(v)$ are described, together with worked examples.

Section fifteen. Empirical Equations.—This deals with the graphical presentation of experimental data, but it is stressed that the equations discussed apply only to non-periodic functions.

Section sixteen. Nomography.—Considerable space is devoted to this important branch of graphics. The various examples of graphical representation are set out in a clear and concise manner and form a most useful introduction to the subject.

Section seventeen. Graphic Statics.—This covers that part of mechanics dealing with balanced force systems. Vectors representative of forces in equilibrium are covered and examples are given of the application of graphics to the solving of problems of plane and space frameworks.

Section eighteen. Graphical Calculus.—This is a very interesting section and the treatment of the subject matter is extremely good. The text deals with problems of area, volumes, centroids, moments of inertia, velocities, accelerations, displacements, etc., and describes methods whereby they may be solved by graphical integration and differentiation.

Section nineteen. Graphics in Research. — A small section which illustrates by photographs and diagrams examples of the application of graphics to research. The examples quoted are mainly concerned with problems associated with artificial limb design and enable the mechanics of leg motion to be pictorially recorded.

The Appendix is most extensive; it covers some 160 pages, and includes a most valuable Bibliography.

The Appendix contains details of basic geometrical construction usually found in standard geometry text books, tables of logarithms and trigonometrical functions, data on American Standards, limits, bolts, nuts, screws, etc. Considerable space is devoted to American Standard Drawings and Drafting Room Practice and there is also a list of graphical symbols for use on drawings.

Several factors have to be taken into account when assessing Professor Levens' book. The first is the price, which at 56s. is by no means excessive when one considers the scope of the work although many students might be deterred from purchasing it on that account.

Secondly, its value to teaching staffs of technical colleges and institutions. Here it might more than prove its worth as each section containing problem sheets for use with this one has already been published.

The third factor is that of presentation. The general level of the text, diagrams, photographs and half tone illustrations is extremely good and reflects great credit upon the publishers.

The book should certainly find a place on the bookshelves of engineers and technical libraries.—E. J. MANN.

TECHNISCHE DYNAMIK. *Vols. I and II. C. B. Biezeno and R. Grammel. In German. Springer, Berlin, 1953. 699+452 pp. Diagrams. DM. 110.*

ENGINEERING DYNAMICS. Vol. I. Theory of Elasticity. *C. B. Biezeno and R. Grammel. Translated by M. L. Meyer. Blackie & Son Ltd., London, 1954. 307 pp. 50s.*

The complete German work and half of the English translation are reviewed together, as there is no difference in the material contained.

Speaking of the quality of the translation one must say that the book has not derived the full benefit of it, namely to become more readable. (It is well known that German books are far more readable in English, especially books on philosophy.) Some of the sentences are too faithful translations from the German original.

As to the edition itself, one is pleased to see that the Springer publications have regained their well known high standard, although the paper of the English edition is of a better quality.

The present publication is a two-volume second edition of the work already well known on the Continent in its first edition, which appeared in 1939 and was subsequently translated into many languages. For those familiar with the first edition it may be sufficient to indicate the distinction of the second.

A section on a non-linear equivalent to Hooke's Law applicable to small strains has been added, introducing methods by which some light alloys can be stressed with greater refinement. Another new section deals with the methods of G. Temple for finding the limits of characteristic numbers of certain differential equations in the theory of structures. The moment distribution method of H. Cross and the relaxation methods of R. V. Southwell have a full discussion with instructions and examples in seven new sections.

Among experimental methods for strain measurement the current preponderance of electric wire resistance strain

gauges has led to a new section on the subject. Much new material has been added to the section dealing with the analysis of a beam resting on several elastic supports.

Four new sections discuss new findings in the analysis of plates loaded in their own plane, namely the semi-infinite plate, the infinite plate with a hole loaded at its periphery, and the infinite plate with two holes. The analysis of the turning of symmetrical rings inside out has been brought up to date.

The section on the general equations of elastic shells has been reformulated and two sections added dealing with the problems of effective width of ring frames and the analysis of ring frames in stiffened cylindrical shells.

A new section has been introduced dealing with a certain class of problem in elastic stability where a beam is associated with a stiff T-bar subject to compression (buckling under " scissor " action).

Another new section in the field of elastic stability concerns buckling associated with tension forces acting on stiff cross-members of a beam.

New material has been added to the section dealing with helical springs and deals in particular with their buckling problems and their analysis under combined compression and torsion.

A further new section concerned with elastic stability discusses the analyses of " scissors action " on stiff hubs or rims of circular plates.

Finally three sections on the centrifugal pendulum have been added to the chapter on torsional vibrations.

Readers not familiar with the first edition of the work should realise that if in exercising their German they translate the title by the phrase " Engineering Dynamics," they would be as misguided about the contents of the book as the German reader must be without looking at its list of contents, for the book deals as much with the analysis of structural elements under static loads as it does with the problems of vibration and mass balance. The only justification for the misleading title is that the whole work is written mainly for the designer and technician in mechanical engineering and discusses particularly elements and problems found in machines.

For those concerned mainly with the solution of problems arising in practical design, the second volume—dealing with the dynamics of steam turbines and internal combustion engines—is distinguished from similar English books on vibrations and balancing in its comprehensiveness, methods and level of treatment. The first volume, on fundamental conceptions and on the stressing of forms typical of machine components, offers from the very extensive literature on the subject a selection not adopted in any English book known to this reviewer. The principle of selection is that of applicability to mechanical engineering.

There are of course some criticisms to offer. One cannot help feeling generally that the mathematics in this work could in many instances be more economically organised, giving it a less forbidding appearance. The rigour and universality of the introduction on the general laws of elastic behaviour do not seem to be entirely justified by the use made of them in the rest of the book. An introduction into the theory of small strains by way of the theory of large strains, apart from its inherent interest, does not appear to have further application in the book. This list could be extended and would undoubtedly be influenced by individual taste. Thus, this reviewer finds the authors' survey of energy theorems unnecessarily cumbersome, but a brief general introduction to the problems of elastic stability unusually penetrating and lucid.

The absence of information derived from experimental research is particularly noticeable in the treatment of certain problems of elastic stability. The behaviour of tubular shafts in torsion and of thin plates loaded in their own plane may be cited as examples.

Perhaps the only really serious criticism is that the classical authority of this book in analytical matters is not matched by sufficient reference to experiment and to all those fields of inelastic behaviour which must be kept in the foreground of interest precisely by those to whom the approach of the present book will most thoroughly appeal. For instance, a very thorough treatment of the elastic behaviour of rotating discs should be clearly accompanied to-day by the practical implications of inelastic behaviour without which no refinement in the design of discs is profitable.

This work covers 1,150 pages and contains in effect, apart from the general introduction and several special introductions to individual classes of problems, a collection of typical and important problems and their detailed solutions, often with extensive numerical examples. Whoever has tried to find in the literature of applied mechanics a solution to a particular problem arising in original design has always experienced the rapid shrinkage of this vast mass of literature often to vanishing point. It would be easy for any reader with this experience, including the reviewer, to find instances within his own sphere of interest where the present work is disappointing. Other instances could be listed which make this reviewer feel a fool who has spent much time and effort solving problems with belated originality, and again others wherein the study of the book has been a minor revelation and will perhaps save the reader from being a fool once more. It is in the last category that the value of this work lies, a value, needless to say, which could not be reproduced by any form of card indexing which ignores associations of reasoning not seen in advance.

ENGINEERING DYNAMICS. *Vol. III. Steam Turbines. C. B. Biezeno and R. Grammel. Translated by E. F. Winter and H. A. Havemann. Blackie, London, 1954. 264 pp. Diagrams. 40s.*

This book deals comprehensively with the " dynamics " of rotating discs, turbine blades and shafts. By " dynamics " the authors seek to restore the original meaning of the word as defined by Kirchhoff, thereby including " statics " and " kinetics." The book assumes that the reader knows his elementary mechanics and the pure mathematics that goes with it.

The book is divided into three main sections. Part I, dealing with rotating discs, considers first of all the systems of stresses acting on discs of various geometric profiles and goes on to consider the radial extension of such discs. An example of an arbitrary, but practical, disc profile is worked out in detail, by breaking the disc down into suitable annuli. A very practical tabular chart is given at the end of the book. Torsional and radial vibrations of discs are next considered. Torsional vibration characteristic values are obtained graphically, while tabular methods are used for the radial oscillations, and a small section is devoted to the torsional vibration of a shaft carrying discs.

Finally in this section, and probably of more interest to gas turbine engineers, the flexure and flexural vibrations of rotating discs are considered at some length. Rayleigh's method is developed for use with both the umbrella and fanwise vibrations and this method is extended by the application of successive approximation and estimation of

errors. Galerkin's method is not recommended by the authors for the calculation of disc vibrational frequencies.

Part II is entitled "turbine blades,' and is obviously written from the steam turbine engineer's point of view but has much of interest for the axial compressor engineer. The bending and stretching of blades without and with lacing wires or shrouds is considered briefly, including the effect of centrifugal force on blade bending. Radial flow turbines are also briefly mentioned in this section.

The theory of flexural vibrations of blades is treated very fully. Simple theory for a uniform blade with no centrifugal force is used to demonstrate the differential equation method, Rayleigh's method, Galerkin's method, a counterpart of Galerkin's method developed in the earlier volume I, and finally the integral equation method. This small section can be recommended for a simple and clear development of these methods. The application of these methods to non-uniform blades is then developed, blade areas and moments of area being approximated by simple functions. Finally the theory is built up to include rotating, staggered blades with shrouds. The stagger angle is discounted after a brief discussion, but this should only be done for hub/tip ratios approaching unity. With small hub/tip ratios the stagger angle *can* have an important effect on fundamental frequency. Two general examples are worked out and Part II concludes with a small section on radial flow turbine blade vibration. Torsional vibration of blades is not considered.

The third and final section of the book deals with critical speeds of rotation, torsional vibration having been dealt with in Part I. Firstly, the critical speed of a shaft carrying a single disc is derived and friction on the surface of the disc is shown to diminish the danger of the critical state. The effect of elastically supported bearings and the oil cushioning in the bearings leading to "' oil whip" is demonstrated. The effect of a small axial force and torsional moment on the critical speed is derived in a simple formula. Second-order criticals due to periodic fluctuation in the driving moment are found in terms of the first-order critical speed. The gyroscopic action of the disc is studied, and the whole work is extended to a multiplicity of discs. A practical numerical example is worked out and iterative methods for higher critical speeds are described.

In general this book contains an immense amount of information and is an excellent guide as to method.—J. F. W. PARRY.

ENGINEERING DYNAMICS. *Vol. IV. Internal Combustion Engines. C. B. Biezeno and R. Grammel. Translated by M. P. White. Blackie, London, 1954. 282 pp. Diagrams. 50s.*

The greatest defect of this, the final volume of the series, is in the title, which should be "Internal Combustion Engine Crankshafts." This subject is covered with typical Germanic thoroughness but practically nothing else is dealt with.

The book is divided into three parts. Part I on inertia forces is of seven chapters, starting with the usual Fourier analysis of the connecting rod crank assembly of the one-cylinder engine and building up the formulae for multi-cylinder engines. The consideration of unequal piston weights is deliberately excluded on page 1 as being only applicable to steam engines, but Chapter 3 on engines with special features covers not only unequal crank offset angles, offset cylinders and rotating balance weights but also unequal cylinder spacing, in which it is shown that moment balancing is possible with an odd number of cylinders by this method. Chapter 4 includes a brief discussion of opposed piston engines with two crankshafts, but engines using links or rockers are not considered. The remaining chapters of this section deal with more complex layouts, finishing with rotary and contra-rotating engines.

Part II on power smoothing consists of only two long chapters, the first and longer being on the one-cylinder engine. Here the strictly dynamical approach of the authors is well shown by the fact that the indicator diagram is merely named and not discussed in any way and it does not appear in the index. Friction and the potential energy due to movements of the parts under gravity are considered. In the second chapter multi-cylinder engines are discussed in much the same order as in Part I.

Part III on torsional vibration is of eleven chapters and the treatment will probably be unfamiliar to English readers. It is more elaborate than the methods used in British aero-engine design, giving much attention to several points not usually considered here. Firstly, "induced torsion," *i.e.* the effects of the fact that torsion of crankshafts really includes some bending which causes deflections at one crank-throw to affect neighbouring throws; it appears that this can seriously affect the frequencies of higher modes of vibration. Secondly it discusses the splitting of frequencies due to the variation of effective moment of inertia with position of the cranks. Thirdly, the seventh chapter includes a discussion of "pseudo-resonance," *i.e.* resonant frequencies at which it chances that the vector polygon of the existing forces has theoretically no resultant. It is admitted that the practical value of this phenomenon has not been so great as was originally hoped. The whole of this part appears to put more emphasis on calculation of frequencies in advance of engine testing than was usual in this country on aero engines. On large marine Diesel engines this approach may well be justified.

Considerable attention is paid to coupled engines and engines with split drives. The last chapter gives a relatively simple discussion of pendulum absorbers.

Throughout the book considerable attention is paid to two-stroke engines and in-line engines with odd numbers of cylinders.

Although the preface implies that the series is written for post-graduate engineers, the treatment seems far more suited to mathematicians, as is not unusual with Continental works. It would be presumptuous for an engineer with fading memories of piston engines to seek for errors of detail.

The notation is elaborate and consistent throughout the book, but there are no lists of symbols and few numerical examples.

The translation has the great merit of eliminating the flavour of German syntax which is so often evident in works of this kind. It is made from the second German edition of 1953; there is no indication of how much this differs from the original edition of 1939, which might be taken to imply that the difference is small.

For the Diesel engine designer of sufficient mathematical background this will be a valuable work of reference, to the aero-engine designer it can only be an important historical document.—C. L. JOHNSON.

MECHANICAL FAILURES OF METALS IN SERVICE. *John A. Bennett and G. Willard Quick. National Bureau of Standards Circular 550. U.S. Government Printing Office, Washington 25, D.C., 1954. 36 pp. 102 figures. 30 cents.*

The National Bureau of Standards has taken in this circular 35 representative cases of failure and presented the factors of design, fabrication or use contributing to

the failures. Characteristics by which the various types of fracture may be recognised are discussed and suggestions for their avoidance put forward. The booklet is well illustrated and six references for more detailed reading are given.

ROTARY WING AIRCRAFT HANDBOOKS AND HISTORY. *Edited by Eugene K. Liberatore. U.S. Dept. of Commerce.*

The U.S. Department of Commerce is publishing and distributing a set of handbooks which was compiled for the Air Force by the Prewitt Aircraft Company and edited by Eugene K. Liberatore. The volumes are unclassified, are in report form and will be available to the general public at a nominal price. Copies of Volumes 6, 7, 10, 13 and 14 are now available at a price of $2.00 each. Orders should be sent to the U.S. Department of Commerce, Office of Technical Services, Washington 25, D.C., with check or money order made payable to the Treasurer of the United States. The volumes are as follows:—

Volume 1. History of the helicopter to the year 1900, by Eugene K. Liberatore.
Volume 2. Helicopter development, 1900-1938, by Eugene K. Liberatore.
Volume 3. Helicopter development, 1939-1950, U.S.A., by Eugene K. Liberatore.
Volume 4. Helicopter development, 1939-1950, foreign, by Eugene K. Liberatore.
Volume 5. Weights and balance, by Eugene K. Liberatore.
Volume 6. Aerodynamics and performance of helicopters, by Alexander Klemin and Igor A. Sikorsky.
Volume 7. Vibrations handbook for helicopters, by Robert A. Wagner.
Volume 8. Mechanical design and description, by Harris S. Campbell.
Volume 9. Rotor blade handbook, by Eugene K. Liberatore.
Volume 10. Stability and control of rotary wing aircraft, by William E. Cobey.
Volume 11. Special types of rotary wing aircraft, by Eugene K. Liberatore.
Volume 12. Autorotating wings, by Eugene K. Liberatore.
Volume 13. Convertible aircraft, by Eugene K. Liberatore.
Volume 14. The rotary wing industry, by Eugene K. Liberatore.
Volume 15. U.S. patent abridgements, by E. T. Hale, E. K. Liberatore and R. J. Trainor.
Part I, abr. no's. 18,002 to 1,153,073.
Part II, abr. no's. 1,155,485 to 1,713,421.
Part III, abr. no's. 1,713,874 to 2,111,975.
Part IV, abr. no's. 2,111,988 to 2,491,260.
Volume 16. Foreign patent abridgements, by E. T. Hale, E. K. Liberatore and R. J. Trainor.
Part I, abridgements from Australia and Britain (6-1895 to 404,237).
Part II, abridgements from Britain (410,532 to 601,952), Denmark, France, Finland, Italy, Netherlands, Norway, Sweden, Switzerland and Russia.
Volume 17. Subject and inventors index of rotary wing aircraft patents of the world, by Eugene K. Liberatore.
Volume 18. Bibliography of rotary wing aircraft, by Eugene K. Liberatore and Elizabeth S. Zimmerman.

These volumes are not yet available in the Library.

U.S. AND CANADIAN MILITARY AIRCRAFT RECOGNITION, 1955. *88 pp. Illustrated. 2s. 6d.*
AIRCRAFT TODAY, 1955. *104 pp. Illustrated. 9s. 6d.*
Both edited by J. W. R. Taylor and published by Ian Allan Ltd.

The firm of Ian Allan Ltd. have produced "recognition" books on all subjects—trains, omnibuses, commercial vehicles, cars and aircraft. The booklets are remarkable for the amount of information given and for their reasonable cost. No schoolboy can afford "Jane," but there are few, with present day economics, who cannot "raise" half-a-crown—at any rate at the age when they can appreciate these books.

"Aircraft Today" is different but the team of contributors Mr. Taylor has assembled—Lithgow on Jets; Wills on Gliding; Hafner on Helicopters, to name a few—make this remarkable value and a first-rate present for a boy.

DOWN IN THE DRINK. *Ralph Barker. Chatto & Windus, London, 1955. 253 pp. Photographs. 12. 6d.*

Here are eight factual stories—each with a different setting but with one thing in common—rescue from the sea after "ditching"; hence the sub-title, "True Stories of the Goldfish Club." The unbearable suspense of the first story, "Ferry Flight," is not, thank goodness, found in any of the subsequent stories but each has its offering of sheer guts and tenacity on the part of the survivors and many have evidence of the amazing patience of Air/Sea Rescue in its determination to get ditched men home again. The tragedy of "The Balance Sheet" leaves one aghast even after the excitement of the victory over the Germans who were matching themselves against our rescuers. "Winkie and Stinkie" pays tribute to the pigeons who probably did more towards saving lives than most people realise, and "Last out of Java" makes one wonder how men of the calibre of Sergeant Tottle fill such lowly places in the Royal Air Force. It also makes one wonder how such chaos as existed in Java went unpunished.

Postscripts to each story giving the subsequent history of the persons involved give an added interest.—F. H. S.

PROCEEDINGS OF THE SOCIETY FOR EXPERIMENTAL STRESS ANALYSIS. *Vol. XII. No. 1. Edited by C. V. Mahlmann and W. M. Murray. Published by the Society for Experimental Stress Analysis, 1954. 226 pp. Illustrated.*

One can expect to find something of interest in any volume of the Proceedings of the Society for Experimental Stress Analysis, and Volume XII, No. 1 does not disappoint. This number contains a lecture on stress concentration by Timoshenko and twenty-one contributions. Six of these are on photoelastic techniques, the rest being divided between strain measurements, and measuring techniques, materials testing methods, and structural analysis, and two of these twenty-one contributions will be completely new to most readers in this country.

Timoshenko's William Murray lecture is a good correction for any tendency to insularity, but there is one person, neglected in America, who surely deserved mention. Filon's "generalised plane stress" is the only complete treatment of the basic theory relevant to photoelasticity. He could also claim a wide selection of stress distributions to his credit.

The average reader is fortunate in that nearly all the Russian work quoted has been published independently at about the same time largely in the proceedings of the Royal Society.

The paper on the barium titanate strain gauge (p. 117) deserves to be widely read. It might stimulate demand for this type of gauge in this country although some development work is still needed. As shown in Fig. 1 the gauge measures the strain sum, $\varepsilon_x + \varepsilon_y$, and we are not told how this measurement was utilised at Stanford University, but it seems probable that only uni-axial stress systems were investigated.

The other completely new contributions are the papers from the Naval Research Laboratory on isopachics from interference patterns. These papers will send many people into their laboratories to try out these techniques which promise to be quicker, cheaper, and simpler than any other method of two-dimensional stress separation. Certainly, commercial Perspex exhibits the type of fringes described by Mr. Post in the first paper, and if he had been more precise on the optical and photographic details we would have been even more indebted to him.

The method of the second paper seems superior to the first and must go a long way to overcome the resistance to interference methods that seems general in this country.

The paper on elliptic pressure tubes raises an important point of principle. Any comparison of experiment with theory surely aims at establishing the conditions under which the original assumptions are justified. Comparison of one stress only from each model is not an adequate way

of doing this. It is a serious criticism that comparison is made only for small values of S/P with wide ellipses and large eccentricities.

The analysis of multi-barrel conduits is a very competent piece of work. There is however no mention of the notorious difficulty of obtaining accurate measurements of fringe order at a boundary, especially with Catalin. These readings are likely to be low. "Relaxation methods" have few adherents in this country for obtaining the stress sum, and it is extremely unlikely that the method had any advantage over integration methods, for the results obtained in this paper.

Apart from the original techniques mentioned the papers are about experimental work, very similar to that being carried out in similar establishments in most European countries. America is fortunate in having a prosperous society to cater for and encourage such work. —C. SNELL.

THE DANGEROUS SKIES. *A. E. Clouston. Cassell & Co. Ltd., London, 1954. 187 pp. Illustrated. 13s. 6d.*

Clouston the pilot is courageous, resourceful and worthy of the front rank of his profession, both in peace and in war. By contrast, Clouston the author is a disappointment. With a title almost as naïve as "God is my Co-pilot," "The Dangerous Skies" opens with a text-book-like chapter, describing the Empire Test Pilots' School at Farnborough which Clouston commanded, and then in the next chapter we are told how the author began his flying career. But the would-be reader should not be discouraged by this jumbled start, for the book improves enormously as it goes on, despite a number of irritating howlers such as calling the distinguished scientist Dr. Harold Roxbee Cox (now Sir Harold) "Roxbecox" and referring to two-position non-Hydromatic propellers as "two-speed hydramatic propellers."

The description of flights like the one in the Miles Hawk to Johannesburg, and the Comet out-and-home record flights to Johannesburg and New Zealand are enthralling. For terrifying experiences it would be hard to beat the freezing up of the engines on three successive occasions when flying blind through the Alps, or of letting down into fog-bound Penang aerodrome without any radio, and fuel almost exhausted after a flight of 1,600 miles from Allahabad.

Clouston's operational experience both on fighters and in Coastal Command also makes excellent reading, though his test-piloting includes an unfortunate incident whereby the author took over the test-flying of a prototype, under conditions which he tends to cloak in mystery, but in fact were simply due to the Maker's Chief Test Pilot having been taken seriously ill.

One is left with the impression that Clouston's success in the air is due to a high level of physical skill combined with an outlook which is not restricted by a high level of imagination. "The Dangerous Skies" is certainly worth reading, but it could have been much more so if a little more time had been spent in polishing up the lay-out and detail accuracy of the story.—J. G.

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Reports

AERODYNAMICS

Boundary Layer

The interaction between shock waves and boundary layers. D. W. Holder, H. H. Pearcey and G. E. Gadd. With a note on The effects of the interaction on the performance of supersonic intakes. J. Seddon. C.P. No. 180 (1955).

The inter-action between shock waves and boundary layers has important effects in many problems of high-speed flow. This paper is a guide to the literature on the subject and a critical review of the present state of knowledge of the underlying physical processes and the practical applications.—(1.1.0.3 × 1.2.0.2 × 1.5.1).

Study of the momentum distribution of turbulent boundary layers in adverse pressure gradients. V. A. Sandborn and R. J. Slogar. N.A.C.A., T.N. 3264 (*January* 1955).

Experimental evaluation and analysis were made of mean and turbulent terms of the equations of motion and the stress tensor at four stations in a turbulent boundary layer with a progressively increasing adverse pressure gradient.—(1.1.3.1).

Similar solutions for the compressible laminar boundary layer with heat transfer and pressure gradient. C. B. Cohen and E. Reshotko. N.A.C.A., T.N. 3325 (*February* 1955).

Stewartson's equations for the compressible laminar boundary layer with pressure gradient and heat transfer are solved for pressure gradients varying from that causing separation to the infinitely favourable gradient and for wall temperatures from absolute zero to twice the free-stream stagnation temperature.—(1.1.1.1 × 1.9.1).

Analysis of laminar forced-convection heat transfer in entrance region of flat rectangular ducts. E. M. Sparrow. N.A.C.A., T.N. 3331 (*January* 1955).

The simultaneous development of temperature and velocity profiles in the entrance region of a flat rectangular duct is studied. The flow is laminar with constant properties and negligible dissipation. Two thermal conditions for the duct walls are considered: (1) both walls have the same uniform temperature throughout; (2) one wall is at uniform temperature, the other wall is insulated. Thermal and velocity boundary layers are calculated using the Kármán-Pohlhausen method.—(1.1.1.1).

Experiments on turbulent flow through channels having porous rough surfaces with or without air injection. E. G. Eckert, A. J. Diaguila and P. L. Donoughe. N.A.C.A., T.N. 3339 (*February* 1955).

Experiments were made to study the flow characteristics along porous rough surfaces with and without air injection for turbulent flow in a channel. Four degrees of roughness were studied with ratios of air-injection velocity to main stream velocity from 0 to approximately 0·017. Velocity distributions along the rough porous surfaces and friction coefficients are presented.—(1.1.5.1 × 1.5.1.2).

A fibrous-glass compact as a permeable material for boundary-layer-control applications using area suction. R. E. Dannenberg, J. A. Weiberg and B. J. Cambucci. N.A.C.A., T.N. 3388 (*January* 1955).

The resistance to air flow of fibrous-glass compacts suitable for boundary layer control was measured. The flow resistance is related to the thickness and density of the fibrous-glass compacts. Constant thickness compacts with specified permeability distributions were fabricated and tested.—(1.1.5).

Compressible Flow

See also Boundary Layer

The drag of source distributions in linearized supersonic flow. G. N. Ward. CoA Report No. 88 (*February* 1955).

Most bodies whose wave drags in supersonic flow have been calculated by linearised theory are such that the flows can be represented by a suitable distribution of sources. This paper extends this idea by considering the drag problem for the general class of thin and slender bodies which can be replaced by sources only.—(1.2.3.1).

A vector study of linearized supersonic flow applications to nonplanar problems. J. C. Martin. N.A.C.A. Report 1143 (1953).

A vector study of the partial-differential equation of steady linearised supersonic flow is presented. General expressions are derived which relate the velocity potential in the stream to the conditions on the disturbing surfaces. Problems concerning non-planar systems are investigated, and methods are derived for the solution of some simple problems. The damping in roll is found for rolling tails consisting of four, six, and eight rectangular fins.—(1.2.3.1).

Unsteady oblique interaction of a shock wave with a plane disturbance. F. K. Moore. N.A.C.A., Report 1165 (1954).

Analysis is made of the flow field produced by oblique impingment of weak plane disturbances of arbitrary profile on a plane normal shock. Three types of disturbance are considered: (*a*) sound wave propagating in the gas at rest into which the shock moves, (*b*) sound wave overtaking the shock from behind, (*c*) an incompressible vorticity wave stationary in the gas ahead of the shock. Computations are presented for the first two types of incident wave, over the range of incidence angles, for shock Mach numbers of 1, 1·5 and ∞.—(1.2.3.2).

On the small-disturbance iteration method for the flow of a compressible fluid with application to a parabolic cylinder. C. Kaplan. N.A.C.A., T.N. 3318 (*January* 1955).

The Prandtl-Busemann small-disturbance method is applied to a parabolic cylinder and compared with the Janzen-Rayleigh or M_∞^2-expansion solution for the same shape. The small-disturbance solution for the parabolic cylinder is examined from the point of view of thin aerofoil theory. The series development of the fluid speed at the surface in powers of the ratio of the radius of curvature of the vertex and the abscissa measured from the vertex agrees with the results of second-order thin aerofoil theory.—(1.2.3).

General theory of conical flows and its application to supersonic aerodynamics. P. Germain. N.A.C.A., T.M. 1354 (*January* 1955).

A method of studying the equation of cylindrical waves is particularly indicated for the solution of certain aerodynamic problems. The method reduces problems of a hyperbolic equation to problems of harmonic functions. The study has been applied toward setting up the fundamental principles, to developing their investigation up to calculation of the pressures on the visualised obstacles, and to showing how the initial field of "conical flows" was enlarged by a procedure of integral superposition.—(1.2.3).

Fluid Dynamics

Impingement of water droplets on wedges and double-wedge airfoils at supersonic speeds. J. S. Serafini. N.A.C.A., Report 1159 (1954).

An analytical solution is presented for the equations of motion of water droplets impinging on a wedge in a two-dimensional supersonic flow field with an attached shock wave. The closed-form solution yields analytical expressions for the equation of the droplet trajectory, the local rate of impingement and the impingement velocity at any point on the wedge surface, and the total rate of impingement. The analytical expressions are utilised in the determination of the impingement of water droplets on the forward surfaces of symmetrical double wedge aerofoils in supersonic flow fields with attached shock waves.—(1.4).

Experimental evaluation of momentum terms in turbulent pipe flow. V. A. Sandborn. N.A.C.A., T.N. 3266 (*January* 1955).

Terms of the longitudinal and radial direction turbulent momentum equations were experimentally evaluated in a 4-inch diameter pipe from total and static pressure data and hot-wire anemometer surveys. Direct comparisons were made with turbulence measurements obtained using the constant current and constant temperature systems of hot-wire anemometry.—(1.4.2).

INTERNAL FLOW

See also BOUNDARY LAYER

*Performance of sheet metal bladed ducted axial flow fans. R. A. Wallis. A.R.L. Report A.*90 (*September* 1954).

Experimental data are presented which show that a relatively good efficiency can be obtained with a circular arc bladed fan. The design assumptions are closely approached in practice. The order of the tail fairing losses has been established.—(1.5.2.1).

Sobre el calculo de canales convergentes. G. Moretti. Aeronautica Argentina, Comunicaciones e Informes. C-10 (*November* 1954).—(1.5.1 × 1.12.1.3).

Secondary flows and boundary-layer accumulations in turbine nozzles. H. E. Rohlik et al. N.A.C.A., Report 1168 (1954).

The results of detailed measurements of the high-speed flows in three turbine nozzle configurations are interpreted, with the aid of low-speed flow-visualisation experiments, to establish the sources and patterns of the secondary flows there.—(1.5.3.2).

Prediction of losses induced by angle of attack in cascades of sharp-nosed blades for incompressible and subsonic compressible flow. J. J. Kramer and J. D. Stanitz. N.A.C.A., T.N. 3149 (*January* 1955).

A method of computing the losses in total pressure caused by a non-zero angle of attack at the inlet to a row of sharp-nosed blades is developed for both incompressible and subsonic compressible flow.—(1.5.4.1).

Low-speed wind-tunnel investigation of a triangular sweptback air inlet in the root of a 45° *sweptback wing. A. L. Keith and J. Schiff. N.A.C.A., T.N.* 3363 (*January* 1955).

Results of a low-speed study of a 45° swept-back wing root air inlet configuration believed suitable for transonic speed aeroplanes are presented. The inlet-configuration lift and drag characteristics are compared with those of a basic model. Boundary layer growth along the fuselage nose, inlet total pressure recoveries, and static pressure distributions over the inlet and wing surfaces are presented for wide ranges of inlet velocity ratio and angle of attack.—(1.5.1 × 1.10.2.2).

STABILITY AND CONTROL

See also TESTING AND INSTRUMENTS

Method for calculating the rolling and yawing moments due to rolling for unswept wings with or without flaps or ailerons by use of nonlinear section left data. A. P. Martina. N.A.C.A., Report 1167 (1954).

The methods of N.A.C.A. Reports 865 and 1090 have been applied to this calculation, allowing the use of non-linear section lift data together with lifting line theory. Two calculated examples are presented in simplified computing forms to illustrate the procedures involved.—(1.8.1.2).

The linearized equations of motion underlying the dynamic stability of aircraft, spinning projectiles, and symmetrical missiles. A. C. Charters. N.A.C.A., T.N. 3350 (*January* 1955).

Linearised equations of motion are derived for aircraft with mirror symmetry and for spinning projectiles with both rotational and mirror symmetry. The customary set of dynamic stability derivatives is extended to include the aerodynamic effects of spin. The aircraft and projectile cases are treated alike and the consequences of symmetry and spin are shown by a comparison of the equations for the two cases. Dynamic stability conditions are derived. The equations for spinning projectiles are applied to the analysis of flight test data from the aerodynamics range.—(1.8.0).

Effect of lag of sidewash on the vertical-tail contribution to oscillatory damping in yaw of airplane models. L. R. Fisher and H. S. Fletcher. N.A.C.A., T.N. 3356 (*January* 1955).

Two models were tested which permitted, in effect, a systematic variation of the sidewash gradient at the vertical tail. The unsteady damping in yaw and directional stability parameters are compared with the steady derivatives obtained for the same models to establish the effects of the sidewash and the lag of the sidewash on these lateral stability derivatives.—(1.8.1.2).

Use of nonlinearities to compensate for the effects of a rate-limited servo on the response of an automatically controlled aircraft. S. F. Schmidt and W. C. Triplett. N.A.C.A., T.N. 3387 (*January* 1955).

A method is developed for designing suitable non-linear functions of error into a system to compensate for the undesirable effects of control surface rate limiting on the response of an automatically controlled aircraft.—(1.8.0).

THERMO-AERODYNAMICS

See also BOUNDARY LAYER

Icing limit and wet-surface temperature variation for two airfoil shapes under simulated high-speed flight conditions. W. D. Coles. N.A.C.A., T.N. 3396 (*February* 1955).

The variation of wet-surface temperature and the conditions that will result in ice free surfaces for high speed flight through clouds were investigated experimentally and compared with calculated values obtained with an analytical method.—(1.9.1).

WINGS AND AEROFOILS

See also INTERNAL FLOW

Note on the flow near the tail of a two-dimensional aerofoil moving at a free-stream Mach number close to unity. D. W. Holder. C.P. No. 188 (1955).

The flow near the trailing edge of a two-dimensional aerofoil moving at a free-stream Mach number close to unity is discussed for cases where the effects of viscosity are small. A qualitative argument, which is supported by experimental evidence, suggests that the local Mach number downstream of the trailing-edge shock waves is approximately independent of free-stream Mach number, aerofoil geometry, and incidence.—(1.10.2.1).

Measurement of lift, pitching moment and hinge moment on a two-dimensional RAE 102 *aerofoil. A. S. Batson. C.P. No.* 191 (1955).

The charts of R. & M. 2730 for estimating two-dimensional control derivatives were based mainly on data for aerofoils of 15 per cent. thickness. Supplementary tests have been carried out on a two-dimensional 10 per cent. thick R.A.E. 102 with 20 per cent. and 40 per cent. plain round nosed control surfaces. Lift, pitching moment and hinge moment were determined from balance measurements and from integrated pressure distributions at one section. In most cases, consistent coefficients were obtained by the two methods.—(1.10.2.1 × 1.3).

The center of pressure position at low speeds and small angles of attack for a certain type of delta wing. V. Holmboe. SAAB T.N. 13 (*October* 1952).

A simple method is suggested for estimating the centre of pressure position at low speeds and small angles of attack for delta wings having a "kink" in the leading edge. The method is found to be in good agreement with experimental results. The error in the obtained centre of pressure position depends a little on the wing plan form. Usually the error may be expected to be less than one per cent. of the root chord.—(1.10.1.2).

The method of upwash-cancellation in linearized supersonic wing theory as applied to the double-delta wing with subsonic leading edges. I. Total lift and pitching moment in symmetrical flow conditions. H. Behrbohm. SAAB T.N. 18 (*May* 1953).

In analogy to the well known lift cancellation method in linearised supersonic wing theory an upwash cancellation technique is applied to the double-delta wing, which is derived from a basic triangular wing by turning its leading edge downstream of some point (the kink point) against the oncoming flow. The method is best suited for the determination of total lift and pitching moment of such wings. The results for a variety of double-delta wings with subsonic leading edges are given in the form of tables and systematic curves.—(1.10.1.2).

The method of upwash-cancellation in linearized supersonic wing theory as applied to the double-delta wing with subsonic leading edges. II. Velocity potential and pressure distribution at symmetrical flow conditions. H. Behrbohm. SAAB T.N. 19 (*June* 1953).

The method of upwash cancellation developed in SAAB T.N. 18 is applied to find the disturbance velocity potential and the pressure distribution of the double-delta wing with subsonic leading edges at symmetric supersonic flow conditions. The kink-potential and its partial derivatives are given by analytical expressions which, besides some algebraic terms, contain the complete elliptic integrals of all three kinds. Some numerical applications are given.—(1.10.1.2).

A semi-numerical method for the determination of the disturbance velocity potential and the pressure distribution of double-delta wings with subsonic leading edges in supersonic flow. I. Symmetrical flow conditions. H. Behrbohm. SAAB T.N. 20 (*July* 1953).

A method is given to find the disturbance velocity potential and the pressure distribution of a double-delta wing with subsonic leading edges at supersonic speeds. Using the linearised theory of supersonic flow the method is obtained by splitting off the leading edge singularity of the upwash ahead of the basic triangular wing. As examples the pressure distributions of two wings are calculated. A simplified method easily obtained from the general formulae is pointed out; it gives the local pressures with good approximation.—(1.10.1.2).

A semi-numerical method for the determination of the disturbance velocity potential and the pressure distribution of double-delta wings with subsonic leading edges in supersonic flow. II. Uniform pitch and roll conditions. H. Behrbohm. SAAB T.N. 21 (*August* 1953).

The semi-numerical method developed in SAAB T.N. 20 is now extended to find the disturbance velocity potential and the pressure distribution of double-delta wings with subsonic leading edges in uniform pitch or in uniform roll at supersonic speeds. Numerical examples are given.—(1.10.1.2).

Approximate theoretical pressure distribution due to lift and uniform pitch and roll for double-delta wings with subsonic leading edges at supersonic speeds. V. Holmboe. SAAB T.N. 28 (*March* 1954).

A simple method based on the linear theory is presented for estimating the pressure distribution in the regions influenced by the leading edge kinks of double-delta wings having subsonic leading edges at supersonic speeds. The method is here applied to lift and uniform pitch and roll. The resulting expressions for the pressure coefficients are in closed forms.—(1.10.1.2).

A note on the drag due to lift of rectangular wings of low aspect ratio. E. C. Polhamus. N.A.C.A., T.N. 3324 (*January* 1955).

Methods of estimating the induced drag of low aspect ratio wings are discussed and compared with experiment. The profile drag due to lift is also discussed and a method is developed which relates the effect of aspect ratio on the profile drag due to lift to an "effective" two-dimensional lift coefficient. A simple expression for this effective two-dimensional lift coefficient in terms of the aspect ratio is derived and used to correlate experimental values of profile drag due to lift for rectangular wings in the low aspect ratio range.—(1.10.1.2).

Prediction of downwash behind swept-wing airplanes at subsonic speed. J. De Young and W. H. Barling. N.A.C.A., T.N. 3346 (*January* 1955).

The numerical integration method presented enables a rapid prediction of downwash. The principal effects of the rolling-up of the wake are treated as corrections to the flat-sheet wake. A simple approximate correction for the effect of the fuselage is applied. Computing forms and charts of pertinent functions are included. Agreement with available experimental data is good.—(1.10.1.2).

Some effects of propeller operation and location on ability of a wing with plain flaps to deflect propeller slipstreams downward for vertical take-off. J. W. Draper and R. E. Kuhn. N.A.C.A., T.N. 3360 (*January* 1955).

An investigation has been conducted of the effects of propeller blade angle, mode of propeller rotation, propeller location, and ratio of wing chord to propeller diameter on the ability of a wing with plain flaps to deflect the propeller slipstream downward in order to achieve vertical take-off. The basic model consisted of a semi-span wing with 30 per cent. chord and 60 per cent. chord plain flaps. Two large diameter over-lapping propellers driven by electric motors were used.—(1.10.2.2).

Aerodynamic characteristics of N.A.C.A. 0012 *airfoil section at angles of attack from* 0° *to* 180°. *C. C. Critzos, H. H. Heyson and R. W. Boswinkle. N.A.C.A., T.N.* 3361 (*January* 1955).

The aerodynamic characteristics of the N.A.C.A. 0012 aerofoil section are presented for an angle-of-attack range extending through 180°. Data were obtained at a Reynolds number of $1{\cdot}8 \times 10^6$ with the aerofoil surfaces smooth and with roughness applied at the leading and trailing edges and at a Reynolds number of $0{\cdot}5 \times 10^6$ with the aerofoil surfaces smooth. The tests were conducted in the Langley low-turbulence pressure tunnel at Mach numbers no greater than 0·15.—(1.10.2.1).

Investigation of effectiveness of large-chord slotted flaps in deflecting propeller slipstreams downward for vertical take-off and low-speed flight. R. E. Kuhn and J. W. Draper. N.A.C.A., T.N. 3364 (*January* 1955).

An investigation of the effectiveness of a wing equipped with large-chord slotted flaps and an auxiliary vane in rotating the effective thrust vector of propellers to a near-vertical direction for vertical take-off and low-speed flight has been conducted. The model consisted of a semi-span wing equipped with 60 per cent. chord and 30 per cent. chord slotted flaps. Two large-diameter over-lapping propellers, driven by electric motors, were used. The effect of wing incidence, propeller blade angle, and an auxiliary vane on the ability of the wing equipped with slotted flaps to deflect the propeller slipstreams downward were also investigated.—(1.10.2.2).

Helicopter Aerodynamics

Charts for estimating performance of high-performance helicopters. A. Gessow and R. J. Tapscott. N.A.C.A., T.N. 3323 (*January* 1955).

Theoretically derived charts are presented for use in predicting profile drag—thrust ratios of rotors having hinged blades with $-8°$ twist. The charts are considered applicable to rotor operating conditions in which high tip speed ratios or large rotor angles of attack are encountered; however, they do not include the effects of compressibility. Limit lines showing the conditions of onset of stall are included in the charts, and the effects of blade twist on the stall limits are discussed.—(1.11.3).

A method for studying the transient blade-flapping behavior of lifting rotors at extreme operating conditions. A. Gessow and A. D. Crim. N.A.C.A., T.N. 3366 (*January* 1955).

A method is presented for studying the transient behaviour of the flapping motion, as well as for calculating the steady-state flapping amplitudes of free-to-cone and see-saw rotors operating at extreme flight conditions. The method is general and can be applied to blades of any aerofoil section, mass distribution, twist, plan form, taper, root cut-out, and flapping hinge geometry. Stall and compressibility effects can also be accounted for.—(1.11.3).

Testing and Instruments

See also Internal Flow

Strioscopie quantitative en soufflerie. C. Renet. O.N.E.R.A. Note Technique No. 23 (1954).—(1.12.1.3).

A wind-tunnel test technique for measuring the dynamic rotary stability derivatives including the cross derivatives at high Mach numbers. B. H. Beam. N.A.C.A., T.N. 3347 (*January* 1955).

An experimental technique for measuring dynamic stability derivatives of a model aeroplane in a wind tunnel is

described. A single degree of freedom, feed-back controlled, forced oscillation system was used to measure the stability derivatives which are important in estimating the lateral and longitudinal oscillatory motions of a rigid aeroplane. Some representative experimental data are included.—(1.12.4 × 1.8.0.2).

AEROELASTICITY

Description and analysis of a rocket-vehicle experiment on flutter involving wing deformation and body motions. H. J. Cunningham and R. R. Lundstrom. N.A.C.A., T.N. 3311 (*January* 1955).

Flight tests and a mathematical analysis were made to demonstrate and confirm a type of subsonic flutter involving rigid body motions and wing deformations. A mathematical analysis based on two-dimensional incompressible flow provided a conservative prediction of the air speed at which the low frequency flutter occurred.—(2.0).

Effective moment of inertia of fluid in offset, inclined, and swept-wing tanks undergoing pitching oscillations. J. R. Reese and J. L. Sewall. N.A.C.A., T.N. 3353 (*January* 1955).

Fluid dynamics studies were made of simplified model fuel tanks undergoing pitching oscillations. The tanks were pylon-mounted, centrally-mounted at angles of sweep, and inclined at angles of attack. The effective moment of inertia of the fluid was determined experimentally for the various tank configurations over a tank fullness range from empty to full.—(2).

Some considerations on two-dimensional thin airfoils deforming in supersonic flow. E. Migotsky. N.A.C.A., T.N. 3386 (*January* 1955).

The aerodynamic characteristics of indicially cambered two-dimensional aerofoils in supersonic flow are determined theoretically. The power required to sustain a general time varying chordwise deformation is determined. Stability boundaries are presented for the harmonically oscillating parabolic mode. The thickness distribution of a beam having a parabolic fundamental bending mode, *in vacuo*, is determined.—(2.0 × 1.10.1.1).

AIRPORTS

Evaluation by simulation techniques of proposed traffic-control procedures for the Norfolk terminal area. C. M. Anderson et al. C.A.A. Technical Development Report No. 185 (*January* 1955).

A study to determine methods of expediting air traffic to and from the five major airports in the Norfolk, Virginia, terminal area is described. It was made with the aid of simulation techniques developed jointly by the Franklin Institute Laboratories for Research and Development and the Technical Development and Evaluation Center of the Civil Aeronautics Administration.—(6.5).

Experiments to determine neighborhood reactions to light airplanes with and without external noise reduction. F. S. Elwell. N.A.C.A., Report 1156 (1953).

The objective was to ascertain the neighbourhood reactions to the noise of light aeroplanes flown close to residential properties of varying income levels, population densities, and proximity to trade centres, to determine whether the degree of noise reduction found to be practicable produced a significant reduction in neighbourhood objection to such aircraft operations.—(6.4).

FUELS AND LUBRICANTS

Investigation of temperature limitation of various lubricants for high-temperature 20-millimeter-bore ball bearings. Z. N. Nemeth and W. J. Anderson. N.A.C.A., T.N. 3337 (*January* 1955).

Twenty millimetre bore tool steel ball bearings, equipped with either a beryllium copper or an Inconel cage, were operated with liquid and with solid lubricants at temperatures from 100° to 1,000°F. at a speed of 2,500 r.p.m. and a thrust load of 110 lb.—(14.0).

Boundary lubrication of steel with fluorine- and chlorine-substituted methane and ethane gases. S. F. Murray, R. L. Johnson and M. A. Swikert. N.A.C.A., T.N. 3402 (*February* 1955).

Sliding-friction experiments were made with steel surfaces in atmospheres of halogenated gases. Under the conditions of this investigation, the most stable or fully fluorinated gases gave no surface protection. Several fluorinated compounds containing two or more chlorine atoms per molecule served as effective boundary lubricants (reduced friction and prevented excessive wear, surface welding, and metal transfer) in a manner comparable with a conventional liquid lubricant.—(14.3).

HYDRODYNAMICS

Theory and procedure for determining loads and motions in chine-immersed hydrodynamic impacts of prismatic bodies. E. Schnitzer. N.A.C.A., Report 1152 (1953).

A theoretical method is derived for computing the motions and hydrodynamic loads during water landings of prismatic bodies involving appreciable immersion of the chines. A simplified method of computation covering flat-plate and V-bottom bodies with beam-loading coefficients greater than unity is given as a separate section. Comparisons of theory with experiment are presented as plots of impact lift coefficient and maximum draft-beam ratio against flight-path angle and as time histories of loads and motions.—(17.2).

MATERIALS

Lattice strains in 70-30 *brass. J. H. Auld and R. I. Garrod. A.R.L. Report Met.* 7 (*October* 1954).

Experiments have been made in an attempt to assess the influence of intergranular stresses, macroscopic stresses and deformation faults on the residual lattice strains observed in polycrystalline specimens of 70-30 brass after various amounts of plastic extension. The values obtained for the stacking fault probability and the macroscopic strains are so improbable as to throw considerable doubt upon the theoretical basis of the analysis, and emphasise the need for further work to elucidate the origin of these discrepancies and to extend the investigation to other materials.—(21.1).

*Some flexural fatigue tests on 75S-T aluminium alloy sheet specimens with drilled holes. J. M. Finney and J. Y. Mann. A.R.L./SM.*213 (*November* 1954).

Flexural fatigue tests have been made on unnotched specimens of "clad" and unclad 75S-T aluminium alloy and on specimens of unclad 75S-T aluminium alloy with stress concentrations in the form of drilled holes, the values of the stress concentration factors being 1·5, 1·6 and 1·7.—(21.2.2).

Analyse spectrographique des alliages a base de nickel du type 80-20. *F. Malamand. O.N.E.R.A. Publication No.* 73 (1954).—(21.2.0).

The propagation of fatigue cracks in light-alloy plates. W. Weibull. SAAB T.N. 25 (*January* 1954).

Formulae for the propagation of fatigue cracks have been deduced on the basis of an exponential relationship between the rate of crack growth and the nominal stress, and have been verified, except for the initial stage of propagation, on flat, notched specimens of 24S-T, 75S-T and cast Electron.—(21.2.2).

Relation between roughness of interface and adherence of porcelain enamel to steel. J. C. Richmond et al. N.A.C.A., Report 1166 (1954).

Porcelain-enamel ground coats were prepared and applied under conditions that gave various degrees of adherence. The variations were produced by (*a*) varying the amount of cobalt-oxide addition in the frit; (*b*) varying the type of metal-oxide addition in the frit, keeing the amount constant at 0·8 weight per cent.; (*c*) varying the surface treatment of the metal before application of the enamel, by pickling, sandblasting, and polishing; and (*d*) varying the time of firing of the enamel containing 0·8 per cent. of cobalt oxide. A positive correlation was found between adherence and roughness of the interface.—(21.3.1).

Behavior of materials under conditions of thermal stress. S. S. Manson. N.A.C.A., Report 1170 (1954).

A review is presented of available information on the behaviour of brittle and ductile materials under conditions of thermal stress and thermal shock. For brittle materials, simple formulae relating physical properties to thermal-shock resistance are derived and used to determine the relative significance of two indices currently in use for rating materials. A number of practical methods that have been used to minimise the deleterious effects of thermal stress and thermal shock are outlined.—(21.2.0 × 21.3.1).

MISSILES

Shadowgraphs of model projectiles fired at high Mach numbers and near M=1 in the N.P.L. Ballistic Range. W. F. Cope. C.P. No. 189 (1955).

Shadowgraphs of 20 mm. projectiles fired in the N.P.L. Ballistic Range at Mach numbers (mainly) above 3 are shown, and the important features discussed. Shadowgraphs of three rounds whose Mach numbers passed through $M=1$ in their passage down the range are also shown. In all three cases the drag, and in one all the aerodynamic force coefficients, were determined.—(25.2).

POWER PLANTS

Report of the definitions panel on the definitions of the thrust of a jet engine and of the internal drag of a ducted body. C.P. No. 190 (1955).

The problems which occur in defining the thrust of a jet engine and the internal drag of a ducted body are considered and formal definitions and names are given for the concepts considered to be of importance.—(27.1).

Ingestion of foreign objects into turbine engines by vortices. L. A. Rodert and F. B. Garrett. N.A.C.A., T.N. 3330 (*February* 1955).

The ingestion of foreign objects by vortices formed between engine inlet and ground surface was investigated with a 5,000 lb. thrust axial flow jet engine. Vortex formation depended on engine speed, engine height, and surface wind. —(27.1).

Methods for rapid graphical evaluation of cooled or uncooled turbojet and turboprop engine or component performance (effects of variable specific heat included). J. B. Esgar and R. R. Ziemer. N.A.C.A., T.N. 3335 (*January* 1955).

Curves based on the thermodynamic properties of air and combustion gases for a hydrogen carbon ratio of 0·167 are presented to relate parameters affecting each engine component. The curves cover a range of flight Mach numbers from 0 to 3·0, compressor pressure ratios from 1 to 30, turbine-inlet temperatures from 1,500° to 3,000° R. and after-burner temperatures from 2,800° to 3,500° R.—(27.1).

PRODUCTION ENGINEERING

Plastic tools for aircraft production. P. K. Digby and W. J. Paul. CoA Report No. 87 (*January* 1955).

The use of thermo and setting plastics for drop hammer and double curvature panel drill jigs is examined over a wide technical and economic field to establish a sound foundation for investigating the suitability of plastics for tooling. Tools were designed to isolate the variable parameters and a study of their behaviour has begun with the assistance of high-speed filming, to ascertain the limitations of the various materials.—(28).

PROPELLERS

The effects of various parameters, including Mach number, on propeller-blade flutter with emphasis on stall flutter. J. E. Baker. N.A.C.A., T.N. 3357 (*January* 1955).

The effect of many parameters significant to wing flutter as well as blade twist was studied on several untwisted rotating models to determine their significance with respect to propeller stall flutter. The minimum values of the flutter-speed coefficient were found to be slightly greater than 1·0 at subcritical Mach numbers.—(29.8).

REFERENCE LITERATURE

Journées de mécanique des fluides. Publication Scientifique et Technique du Ministère de L'Air. No. 296 (1955).—(30.2).

STRUCTURES

LOADS

The analysis of the structural behaviour of guyed antenna masts under wind and ice loading. Part I: Structural Analysis. G. J. Schott and F. R. Thurston. Part II: Wind Loads. P. J. Pocock. N.R.C.C., Report No. MM-238 (November 1954).

An analytic procedure is described for computing the distribution of bending moment, shear, axial load and deformation in the mast, and the loads in the guy wires, for a 3-level, 4-way guyed antenna mast erection subjected to wind load, ice accretion and loads applied by an antenna installation at the head of the mast. The computational procedure is described explicitly, with examples, and permits the immediate use of normal computational aids.—(33.1.1 × 33.2.4.4).

Analysis of landing-gear behavior. B. Milwitzky and F. E. Cook. N.A.C.A., Report 1154 (1953).

The behaviour of the conventional type of oleo-pneumatic landing gear during the process of landing impact is studied theoretically. The basic analysis is presented in a general form and treats the motions of the landing gear before and after the beginning of shock-strut deflection.—(33.1.2).

Gust-load and airspeed data from one type of four-engine airplane on five routes from 1947 *to* 1954. *W. G. Walker. N.A.C.A., T.N.* 3358 (*January* 1955).

The results are presented of an analysis of approximately 100,000 hours of *V-G* data from one type of four-engine civil transport aeroplane to determine the magnitude and frequency of occurrence of the gust loads and gusts.—(33.1.1).

THEORY AND ANALYSIS

See also LOADS

An experimental investigation into some of the problems associated with stress diffusion in the vicinity of chordwise cut-outs in the wing, and a comparison with existing theories. LaVerne W. Brown. Cranfield Report No. 83 (*September* 1954).

Tests were made on a large stringer-skin panel bounded by constant area edge members and subjected to concentrated, equal end load. Typical dimensions were used; thick skin, multiple stringers, spar cross-sectional area equal to panel area. In these tests variations were made in the lateral stiffness of the spar booms, the method of attachment of the end rib to the spar, and the loading between spar and sheet. —(33.2.4.9.8).

Diffusion of antisymmetrical loads into, and bending under, transverse loads of parallel stiffened panels. J. H. Argyris. R. & M. 2822 (*May* 1946, *published* 1954).

The general theory of diffusion of antisymmetrical concentrated end loads and edge loads into parallel stiffened panels is considered, including the theory of bending of a parallel stiffened panel under arbitrary transverse loads. By combining these results with the results on diffusion of symmetrical loads given in R. & M. 1969 and R. & M. 2038 or in Appendix 1 to this paper it is possible to analyse the diffusion in a parallel panel under any arbitrary load or edge stress distribution.—(33.2.4.6.1).

The effect of uniformly spaced flexible ribs on the stresses due to self-equilibrating systems applied to long thin-walled cylinders. E. H. Mansfield and M. Fine. R. & M. 2832 (*August* 1947, *published* 1954).

In many problems relating to the stressing of thin-walled cylinders, and in particular those concerned with the stresses set up in a cylinder under torsion when one section is restrained against warping, it has been commonly assumed that sections have their shape retained by closely spaced stiff ribs. In this report the effect of discrete, flexible ribs has been investigated and the results have been incorporated in a number of graphs which show the effect of rib-flexibility in a long thin-walled cylinder of arbitrary shape under end constraint.—(33.2.4.3.0).

The flexural axis of thin-walled sections that have no plane of symmetry. D. Williams. B. V. S. C. Rae. R. & M. 2939 (*May* 1943, *published* 1955).

The procedure of finding the flexural axis of unsymmetrical thin-walled sections is simplified obviating the necessity for first finding the principal axis of inertia.—(33.2.4.1).

Pandeo y pandeo-flexion de trenes de barras. F. Heintzelmann. Aeronautica Argentina. Comunicaciones e Informes. 1-1 (*April* 1954).

This paper determines the bending moment equations of beam-columns, or series of beam-columns, and determines the buckling load by stating the buckling conditions.—(33.2.4.1).

Static strength tests on an "Olympic" glider mainplane spar. I. S. Milligan and A. O. Payne. A.R.L. Structures and Materials Note 210 (*August* 1954).

A series of strength tests was carried out on the wing beam of an "Olympic" glider which was designed by members of the Victorian Motorless Flight Group. The beam was a wooden box spar, the booms of which were of mountain ash and it had a minimum number of internal stiffening blocks, the webs being stabilised to a large extent by external stiffeners.—(33.2.4.1).

The deformation analysis of tapered swept wings. A. H. Hall. N.A.E. Report 20 (1953).

A method is outlined for applying the deformation relations derived in N.A.E. Laboratory Report LR-28 for wings without taper, to the analysis of wings with a moderate degree of taper. The experimental results for wing models of cellulose acetate yawed at 0 degrees, 30 degrees, 45 degrees and 60 degrees were used. The unswept plan form of these models provided, approximately, an aspect ratio of 3·5 and taper ratio of 0·5.—(33.2.3.2).

A new method for the statistical treatment of fatigue data. W. Weibull. SAAB T.N. 30 (*May* 1954).

A new life scale for the representation of *S-N* curves is introduced for the purpose of estimating the scatter of fatigue strength as a function of fatigue life. Methods for converting lifetime distributions into strength distributions are proposed.—(33.2.4.0.10).

The static strength and the fatigue strength of riveted, spot-welded and redux-bonded joints in 24 *ST aluminium alloy sheet. W. Weibull. SAAB T.N.* 31 (*June* 1954).

The ultimate tensile strengths and the fatigue lifetimes of five different joints have been determined and compared with corresponding values for plain specimens.—(33.2.4.13.10).

THERMODYNAMICS

*Formation et depot de carbone dans les foyers de turbo-machines d'aviation. C. Fouré. Agard Memorandum AG*12/*M*8 (*May* 1954).—(34.1.1).

Prediction of flame velocities of hydrocarbon flames. G. L. Dugger and D. M. Simon. N.A.C.A. Report 1158 (1954).

The effects of four combustible-mixture variables on the laminar flame velocities of hydrocarbon-oxygen-nitrogen mixtures are predicted by semi-theoretical methods based on (*i*) Semenov equation (thermal mechanism), (*ii*) Tanford-Pease equation (active-particle-diffusion mechanism), and (*iii*) Manson equation (momentum-pressure-drop equation using active-particle concentrations). Empirical equations are summarised which give better predictions, but require more constants.—(34.1.1).